Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production

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1. Accelerator Driven Systems and Their Applications

1.1 History of Accelerator Driven System Activities

Since the early 1990's, accelerator driven systems (ADS) – subcritical assemblies driven by high power proton accelerators through a spallation target which is neutronically coupled to the core – have been proposed for addressing certain missions in advanced nuclear fuel cycles. Institutes throughout the world have conducted numerous programs evaluating the role of ADS in nuclear waste transmutation and energy production. In 1995, the National Research Council (NRC) issued a report on transmutation technologies [1], which included an evaluation of one ADS concept that was under study at that time: a large-scale system that proposed using a ~100-MW accelerator to drive a thermal, molten salt subcritical core. The NRC recognized the numerous complexities associated with the system, including the fact that, at that time, much of the high-power accelerator technology required for that ADS system had yet to be demonstrated. Consequently, the NRC report did not look favorably upon ADS.

In 1999 the US Congress directed the DOE to evaluate Accelerator Transmutation of Waste (ATW) concepts and prepare a "roadmap" to develop the technology. This roadmap [2] identified the technical issues to be resolved, assessed the impact of ATW on high-level waste disposition, and estimated the scale and cost of deploying ATW to close the fuel cycle. It also recommended that Congress fund a $281M six-year program of trade studies and R&D on key technology issues that would support a future decision on technology demonstration.

From 2000 to 2002, the DOE sponsored the Advanced Accelerator Applications (AAA) program to investigate the use of ADS in "closed" nuclear fuel cycles. In 2003 the AAA program transitioned into the Advanced Fuel Cycle Initiative, and DOE-sponsored ADS research ceased, except for the continuation on a few international collaborative efforts. A number of factors contributed to this decision, primarily the small expected growth in commercial nuclear power which "negated" the principal driver for ATW/AAA, i.e., destruction of transuranics and problematic fission products assuming that there would be essentially no new construction of commercial reactors.

Outside of the USA, research into ADS for both transmutation and power generation has not only continued but accelerated. In 2001 the European Technical Working Group evaluated the state of ADS technologies and recommended the construction of an experimental ADS [3]. In 2002 an expert group, convened by the Organization for Economic Cooperation and Development's Nuclear Energy Agency (OECD/NEA), authored a comprehensive report entitled *Accelerator Driven Systems (ADS) and Fast Reactors in Advanced Nuclear Fuel Cycles* [4]. In it, they conclude

> "On the whole, the development status of accelerators is well advanced, and beam powers of up to 10 MW for cyclotrons and 100 MW for linacs now appear to be feasible. However, further development is required with respect to the beam losses and especially the beam trips to avoid fast temperature and mechanical stress transients in the reactor."

Technology demonstration is now gaining momentum with the Belgian government's announcement of its intention to construct MYRRHA [5], an 85-MW prototype ADS at the Belgian Nuclear Research Centre, SCK•CEN. The government has committed to finance 40% of the construction cost, and is expending €60M over the next five years to advance the design in preparation for a construction start in 2015. In addition, there are recent indications the Chinese and Indian governments are considering construction of prototype ADS facilities of similar scale. ADS technology development programs exist in Europe, Japan, South Korea, India, China and Russia which are focused on both waste transmutation and power generation.

Finding #1: There are active programs in many countries, although not in the U.S., to develop, demonstrate and exploit accelerator-driven systems technology for nuclear waste transmutation and power generation.

1.2 Applications of Accelerator-Driven Systems Technology

Accelerator Driven Systems may be employed to address several missions, including:

- Transmuting selected isotopes present in nuclear waste (e.g., actinides, fission products) to reduce the burden these isotopes place on geologic repositories.
- Generating electricity and/or process heat.
- Producing fissile materials for subsequent use in critical or sub-critical systems by irradiating fertile elements.

The principal advantages that accelerator-driven sub-critical systems have relative to critical reactors are twofold: greater flexibility with respect to fuel composition, and potentially enhanced safety. Accelerator driven systems are ideally suited to burning fuels which are problematic from the standpoint of critical reactor operation, namely, fuels that would degrade neutronic characteristics of the critical core to unacceptable levels due to small delayed neutron fractions and short neutron lifetimes, such as ^{233}U and minor actinide fuel. Additionally, ADS allows the use of non-fissile fuels (e.g. Th) without the incorporation of U or Pu into fresh fuel. The enhanced safety of ADS is due to the fact that once the accelerator is turned off, the system shuts down. If the margin to critical is sufficiently large, reactivity-induced transients can never result in a super-critical accident with potentially severe consequences. Power control in accelerator-driven systems is achieved through the control of the beam current, a feature which can be utilized for fuel burnup compensation.

Finding #2: Accelerator-driven sub-critical systems offer the potential for safely burning fuels which are difficult to incorporate in critical systems, for example fuel without uranium or thorium.

1.2.1 Transmutation of Nuclear Waste

The US nuclear industry operates on a "once through" nuclear fuel cycle. All of the used fuel (currently about 60,000 metric tons) is stored on the sites of operating nuclear plants, with about 2,000 metric tons added each year. The President has convened a Blue Ribbon Commission on America's Nuclear Future to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of used nuclear fuel.

One option offering several potential benefits is to recycle the used LWR fuel. The benefits of recycling are i) better resource utilization and a reduction in the amount of uranium that must be mined, and ii) a substantial reduction in the volume, heat load, and radiotoxicity of the high-level waste that must ultimately be emplaced in a geologic repository.

France, Great Britain, Russia and recently Japan have major recycling facilities that are capable of reprocessing several hundred tons or more of used nuclear fuel annually. These are large, expensive (~$10B) government-owned facilities that use the PUREX process to extract the U and Pu from the used fuel, which are then recycled as mixed oxide (MOX) fuel in LWRs. The remaining portion of the used LWR fuel is vitrified, and the intent is to place this waste in geologic repositories.

To date no country employs a fuel cycle that destroys the minor actinides (MA) present in used LWR fuel. Minor actinide destruction through transmutation is one mission that ADS are well suited to address. Unlike critical fast reactors which generally incorporate uranium or thorium in the fuel for safe operation, ADS can potentially operate on a pure MA feed stream, meaning a smaller number of ADS can be deployed to burn a fixed amount of minor actinides. ADS can recycle the MA multiple times until it is completely fissioned, such that the only actinide waste stream from these systems would derive from the recycling residuals, which could yield a significant reduction (by a factor of hundreds) in the amount of actinide waste per kW-hr of electricity generated, as compared to a once-through fuel cycle. Because accelerator driven systems do not require fuels containing uranium or thorium, they are more efficient at destroying MA waste – up to seven times more efficient according to one study [6] – than critical reactors, based on grams of minor actinides fissioned per MW-hr of energy generated.

Finding #3: Accelerator driven subcritical systems can be utilized to efficiently burn minor actinide waste.

1.2.2 Power Production

A facility for transmutation of waste would also generate substantial power; the process heat could be utilized to produce another form of energy (e.g. biofuels) or could be used to generate electrical power. Many proposed ADS concepts with the goal of power production [7,8] utilize thorium-based fuel to take advantage of some of its benefits, including greater natural abundance (3-4 times greater than uranium), proliferation resistance, and significantly reduced production of transuranics which are a major source of radiotoxicity and decay heat relative to uranium-based fuel. Both liquid and solid fuel blankets have been proposed. An ADS system based on Th fuel would not require incorporation of fissile material into fresh fuel, and could operate almost indefinitely in a closed fuel cycle.

A limited number of critical reactor concepts based on thorium have been designed and operated (e.g., the Molten Salt Reactor at ORNL, and the Light Water Breeder Reactor at Shippingport). Expanded use of thorium-based fuels is actively pursued in some countries with large reserves of thorium, principally

India, Norway and China. These programs are investigating whether ADS can speed up the deployment of the ^{233}U-Th fuel cycle by breeding ^{233}U, which does not exist in nature.

Finding #4: Accelerator driven subcritical systems can be utilized to generate power from thorium-based fuels

1.3 Accelerator Driven System Technology

An accelerator driven system consists of a high-power proton accelerator, a heavy-metal spallation target that produces neutrons when bombarded by the high-power beam, and a sub-critical core that is neutronically coupled to the spallation target. To achieve good neutronic coupling the target is usually placed at the center of a cylindrical core. The core consists of nuclear fuel, which may be liquid (e.g., molten salt) or solid as in conventional nuclear reactors.

During the 1990's, the Defense Programs Office within the US Department of Energy (DOE) funded the Accelerator Production of Tritium (APT) program to evaluate the efficacy of using high-power accelerators for producing tritium for the US stockpile. Many technical advances in accelerator technology resulting from this program are directly applicable to high-power accelerators for meeting the ADS missions. In addition, the accelerator and target technologies required for ADS applications have much in common with accelerators and targets that have been developed since then for scientific application at spallation neutron sources, and nuclear and particle physics accelerator facilities.

The technology available to accelerator designers and builders of today is substantially different from, and superior to, that which was utilized in early ADS studies, in particular in the accelerator design which was considered in the 1996 National Research Council report [1]. Since the publication of that report there have been several key advances in accelerator and target technology that are summarized here, and explained in more detail in the sections that follow:

- The construction, commissioning and operation of a high-power continuous wave front-end system that meets the beam current performance required for up to 100 mA ADS accelerator system (the Low-Energy Demonstration Accelerator (LEDA) at Los Alamos)
- The construction, commissioning and MW-level operation with acceptable beam loss rates of a modern linear accelerator based on independently-phased superconducting accelerating structures (the Spallation Neutron Source at ORNL)
- The construction and deployment of a wide variety of pulsed and continuous-wave superconducting accelerating structures for proton/ion acceleration over a wide range in particle velocities, which is a key ingredient to achieving high reliability operation
- The high-power beam test of a liquid Pb-Bi eutectic spallation target loop at the Paul Scherrer Institute in Switzerland (the MEGAPIE project).

Perhaps more important, recent analyses of subcritical reactor response to beam interruptions reveal greater tolerance to and therefore more relaxed requirements for beam trips, which had been a key criticism of ADS concepts, as explained below.

This white paper focuses on the accelerator and spallation target technologies needed to support potential ADS missions. Questions on the state of ADS technologies related to the nuclear fuel cycle, such as the types of nuclear fuel that might power an ADS, or the separations technologies needed in a closed or modified open fuel cycle are not addressed here.

2. Accelerator Driven System Requirements

2.1 Accelerator Driven System Missions

The range of applications of ADS technology discussed within the world-wide community span four missions. These missions are ordered in increasing complexity, increasingly stringent beam requirements, greater development time and cost. Presumably, each successive mission would build upon the technological developments of the preceding mission.

- *Transmutation Demonstration* – the demonstration of ADS and transmutation technologies in a flexible research facility in which a subcritical core is coupled to a MW-scale proton accelerator. This requires building a prototypic accelerator, target and fuel blanket to operate with low power density, an order of magnitude lower than an industrial scale facility.
- *Industrial Scale Transmutation* – a facility for transmutation of nuclear waste on an industrial scale. Such a facility would require a beam power of at least 10 MW and as high as 75 MW, depending on the specific design. The produced heat may be utilized without direct connection to the power grid.
- *Industrial Scale Power Generation with Energy Storage* – a power generation facility that utilizes energy storage technology – developed for solar and wind energy – to mitigate lengthy beam interruptions. Such a system could burn minor actinide fuel to also fulfill a transmutation mission, or could burn thorium-based fuel for the purposes of power generation and ^{233}U production.
- *Industrial Scale Power Generation* – a power generation facility that burns either transuranics or thorium-based fuel and is an integral part of the electric grid.

Finding #5: The missions for ADS technology lend themselves to a technology development, demonstration and deployment strategy in which successively complex missions build upon technical developments of the preceding mission.

2.2 Beam Energy, Power and Time Structure

Accelerator-driven systems require beam energy near 1 GeV to maximize the neutron yield per unit proton beam power. As the yield curve has a rather broad maximum, other technological arguments may favor higher or lower beam energy depending on specific design considerations. In particular, a trade-off exists between beam energy and beam current for a given required beam power, which requires technical and cost optimization in the context of a specific design.

A facility for *Transmutation Demonstration*, being primarily a test-bed and research facility, requires a beam power of 1-2 MW to deliver a thermal power of 50-100 MW, depending on the neutron multiplication factor of the subcritical assembly. This can be realized within a broader range of available beam energies, from approximately 0.5 GeV to as much as 3 GeV, with continuous-wave (CW) beams, and perhaps even with a pulsed beam. A representative example of a Transmutation Demonstration facility is the MYRRHA Project [5] in Belgium which calls for a 600 MeV proton accelerator delivering 1.5 MW beam power to a subcritical core with 85 MW thermal power.

Industrial scale systems, being fully optimized with regard to system cost and technology, require beam energies nearer the peak in neutron yield, in the range of ~1-2 GeV. Tens of MW of continuous wave beam power are required, yielding thermal power in the GW range. The range in beam power evident in the existing world-wide designs reflects the range in neutron multiplication factors, thermal power, burn-up compensation requirements and accelerator system redundancy requirements. Representative examples include the JAEA design [9] (1.5 GeV beam energy, 30 MW beam power and 800 MW_{th}), the European Facility for Industrial Transmutation (EFIT) [10], (0.8 GeV beam energy, 16 MW beam power, and several hundred MW_{th}), and the 1999 Los Alamos Accelerator Transmutation of Waste (ATW) design [11] (1.0 GeV beam energy, 45 MW beam power and four 840 MW_{th} subcritical cores).

2.3 Beam Trip Requirements

The beam trip requirements follow from thermomechanical considerations of the spallation target and subcritical assembly and, for power production applications, reliable electrical power delivery to the grid. The maximum number of allowed beam trips of a given duration depends on the design details, including the coolant parameters and characteristics, the coolant system design, the materials used, and the average power densities in the different ADS components.

In the last several years, more thorough and detailed beam trip requirement analyses have been performed based on transient analyses of ADS reactor system components. Three analyses in particular show reasonable agreement on the transient response and resulting beam trip requirements. A JAEA study [12] considered an 800 MW_{th} subcritical reactor driven by a 30 MW proton beam. The analysis considered thermal shock and cycling on the beam window, reactor vessel, inner barrel and turbine system. The resulting beam trip rate limits are 25,000/yr for short beam interruptions (< 5 sec), 2500/yr for interruptions greater than 5 and less than 10 seconds, 250 per year for interruptions greater than 10 seconds and less than 5 minutes, and 50/year for interruptions greater than 5 minutes. A recent MYRRHA study [13] found similar results, yielding beam trip limits of 2500 trips/year for interruptions greater than 1 second and less than 10 seconds, 2500 trips/year for interruptions between 10 seconds and 5 minutes, and less than 25/year for interruptions greater than 5 minutes. These results include a factor of 10 safety margin. A U.S. study performed in 2001 [14] yielded beam trip limits of 1000 trips/year for interruptions longer than 0.3 sec but shorter than 100 sec, and 30 trips/year for interruptions longer than 100 seconds. It is worth emphasizing that these beam trip limits, derived from transient analyses of subcritical reactor components, are two orders of magnitude less stringent than typical values published previously [15]. For power generation applications, the beam trip rate requirements are more stringent, limited to only a few long unscheduled interruptions per year in order to meet reliability requirements set by the demands of commercial power production.

Additional safety-related requirements include safety-class beam shutdown capability, limitations on maximum beam current/power, rate of change of beam current, automatic closed-loop control of the current and the capability of controlled ramping up (or down) the beam power over seconds to minutes.

Finding #6: Recent detailed analyses of thermal transients in the subcritical core lead to beam trip requirements that are much less stringent than previously thought; while allowed trip rates for commercial power production remain at a few long interruptions per year, relevant permissible trip rates for the transmutation mission lie in the range of many thousands of trips per year with duration greater than one second.

2.4 Summary of ADS Parameters

The range of parameters for accelerator driven systems, meeting the four missions outlined above, are shown in Table 1. It is worth emphasizing that the four missions outlined in the Table show a natural progression in technology toward increasing complexity to deliver increasingly stringent beam requirements. The entire progression would require that lessons learned from the previous generation of ADS deployment be incorporated into the next generation – a process that could take place over a period of a few decades.

Table 1: Range of Parameters for Accelerator Driven Systems for four missions described in this whitepaper

	Transmutation Demonstration	Industrial Scale Transmutation	Industrial Scale Power Generation with Energy Storage	Industrial Scale Power Generation without Energy Storage
Beam Power	1-2 MW	10-75 MW	10-75 MW	10-75 MW
Beam Energy	0.5-3 GeV	1-2 GeV	1-2 GeV	1-2 GeV
Beam Time Structure	CW/pulsed (?)	CW	CW	CW
Beam trips (t < 1 sec)	N/A	< 25000/year	<25000/year	<25000/year
Beam trips (1 < t < 10 sec)	< 2500/year	< 2500/year	<2500/year	<2500/year
Beam trips (10 s < t < 5 min)	< 2500/year	< 2500/year	< 2500/year	< 250/year
Beam trips (t > 5 min)	< 50/year	< 50/year	< 50/year	< 3/year
Availability	> 50%	> 70%	> 80%	> 85%

3. Accelerator Technology

A complete accelerator system for high-power (> 10 MW) ADS applications utilizing linear accelerator technology consists of three main sections: i) an Injector System which produces a high-current, continuous, bunched proton beam, ii) an acceleration system which accelerates the low-energy beam from the Injector to energies near 1 GeV with extremely high efficiency to minimize particle loss, and iii) a beam-delivery system which transports the beam to the spallation target, and shapes the beam to the required size, profile, and uniformity.

3.1 Accelerator Requirements

The detailed accelerator requirements vary depending on the ADS application under consideration. Three sets of accelerator requirements from three reference ADS designs are shown in Table 2 to demonstrate the range of parameters. The first column displays requirements for the MYRRHA Project [5] which is aimed at demonstration of transmutation and ADS technologies (as well as serving as an irradiation facility). The second column shows requirements for EFIT [10], which is aimed at industrial-scale prototypic operation of a single subcritical core. The third column shows requirements taken from the Accelerator Transmutation of Waste (ATW) Program [11], an industrial scale facility of higher power with the capability of driving multiple subcritical cores. In each case, proton beam energy near 1 GeV, and a continuous-wave (CW) beam time structure, is required. In order to allow hands-on maintenance of the accelerator beamline components, uncontrolled beam loss must be maintained at levels less than 1 Watt/m, which translates into fractional beamloss requirements (at full energy) ranging from ~1 part-per-million per meter (ppm/m) for a demonstration facility to less than 0.1 ppm/m for an industrial scale facility. Beam current "swing" is required in ADS systems in order to compensate for changes in reactivity during burnup of solid fuel. Beam power stability of +/- 1% is required. In addition, beam size and position stability on the target of less than 10% and 0.1 rms beamsize, respectively, are required. Trip rate requirements vary by mission as was discussed earlier.

Table 2: Accelerator Requirements for three reference ADS Designs

	Transmutation Demonstration (MYRRHA [5])	Industrial Scale Facility driving single subcritical core (EFIT [10])	Industrial Scale Facility driving multiple subcritical cores (ATW [11])
Beam Energy [GeV]	0.6	0.8	1.0
Beam Power [MW]	1.5	16	45
Beam current [mA]	2.5	20	45
Uncontrolled Beamloss	< 1 W/m	< 1 W/m	< 1 W/m
Fractional beamloss at full energy (ppm/m)	< 0.7	< 0.06	< 0.02

3.2 Accelerator Technology Choices

To date, three accelerator technologies have demonstrated proton beam power capability of greater than 1 MW. These include i) the separated sector cyclotron, the highest power example of which operates at the Paul Scherrer Institute in Switzerland, delivering a 1.2 MW continuous-wave beam, ii) the normal conducting proton linear accelerator, the highest power example of which (the LANSCE linac) delivered a 1 MW pulsed beam at Los Alamos National Laboratory, and iii) the superconducting proton linear accelerator, the highest power example of which (the SNS linac) delivers a 1.1 MW pulsed beam at Oak Ridge National Laboratory. The beam power demand of 1-2 MW required to satisfy the demonstration mission outlined in Tables 1 and 2 above can be met by present-day superconducting linac or cyclotron technology.

Alternative approaches to high proton beam power include synchrotron technology, which has the capability of achieving powers in excess of 1 MW, but is limited to pulsed operation at relatively low duty factor. Fixed-Field Alternating Gradient (FFAG) accelerators are actively studied at laboratories throughout the world. Synchrotrons and FFAGs have some similar intrinsic features, but the repetition rate for FFAGs can be much higher (albeit without the capability for true CW operation). While promising, FFAGs have yet to demonstrate high beam-power capability.

For ADS missions requiring beam power in the 5-10 MW range in the CW mode, it is anticipated that both cyclotron (at its limits) and linear accelerator technologies are applicable. With further development, FFAG technology may also demonstrate applicability in this power range. It is worth noting that cyclotron technology is limited to a maximum energy of 0.8-1 GeV. Schemes for combining beams from multiple cyclotrons have been proposed to reach power levels up to 10 MW [16]. However, for ADS missions requiring greater than 10 MW proton beam power, at present, only superconducting linear accelerator technology appears to be practical. Previous studies have concluded that superconducting linear accelerator technology has far greater beam power potential than cyclotron technology and that it is the technology of choice to deliver the tens of MW needed to drive sub-critical cores with thermal powers approaching 1 GW [17].

Superconducting radio-frequency (SRF) linac technology is well-suited to providing the high power continuous proton beams required for an industrial scale application as it achieves minimum capital and operating costs, relative to that utilizing normal-conducting linac technology. SRF technology provides a high RF-to-beam power efficiency due to the low resistive losses of superconducting materials, and has the capability for achieving very high reliability as it lends itself to implementing a robust independently-phased radio-frequency cavity system. It is that latter technology, proposed in European studies and validated in practice at SNS [18] that has the potential for fault tolerance and rapid fault recovery, making use of built-in online cavity spares. Further, there has been tremendous world-wide activity in the last two decades in advancing the performance of SRF accelerating cavity systems, to the point where it is generally considered the acceleration technology of choice in recent and envisioned accelerator facilities requiring high power proton/ion beams (SNS, FRIB, Project-X in the U.S., ESS, SPIRAL-2, MYRRHA in Europe).

Finding #7: For the tens of MW beam power required for most industrial-scale ADS concepts, superconducting linear accelerator technology has the greatest potential to deliver the required performance.

3.3 State-of-the-art

3.3.1 Linac Front-End Systems

The front-end of a high-power proton linac for ADS applications must meet very challenging requirements, namely the delivery of high-current CW beams with extremely high availability. This regime is very different from that of existing accelerators which operate with duty factors in the range of 0.1%-6%. The front-end system typically consists of a high-current proton source, a low-energy beam transport system and a radiofrequency quadrupole (RFQ) accelerator that simultaneously bunches, focuses and accelerates the beams to energies in the range 2-7 MeV.

The Low Energy Demonstration Accelerator (LEDA) project at Los Alamos, the centerpiece of the Accelerator Production of Tritium program, demonstrated 100 mA continuous wave (100% duty) operation of a prototypic front-end, consisting of a high-current electron-cyclotron-resonance (ECR) proton source, space-charge-neutralized LEBT, and a 6.7-MeV 8-meter-long 350-MHz RFQ. LEDA performance at full power was successfully demonstrated in 2000, with the RFQ delivering > 90 mA CW beams at 6.7 MeV for about 110 hours, including 20 hours at 100 mA (a beam power of 670 kW). The APT program was terminated before adequate reliability information or long-term performance could be obtained. A dedicated beam halo experiment was carried out which confirmed the general validity of the particle-core halo model, but also revealed unexplained long tails in the transverse beam profiles in some conditions, which were thought to be the result of beam halo or off-energy particles generated within the RFQ.

Also in the early 2000’s, CEA/CNRS-Saclay developed a test facility (IPHI) to prototype a high-power ADS linac front end up to 10 MeV. An ECR-based injector (SILHI) was built and tested, extracting a 130-mA beam with 85% proton fraction. The source was operated for ~1,000 hours to assess reliability and availability; a 162-hr test in 2001 demonstrated 99.8% availability with no more than one trip per day. IPHI program funding was terminated before the RFQ was built. The IPHI 3-MeV RFQ is now to be completed and operated at 30-mA CW as a reliability/availability test bed within the European (EUROTRANS) program.

Several linac front-end designs capable of providing CW (100% duty) proton currents in the range 30 to 100 mA have been developed over the past 15 years. Ongoing active programs include: i) the IFMIF-EVEDA (Engineering Validation and Engineering Design Activities) program, presently underway in Japan, which intends to prototype and demonstrate the high-power deuteron front-end up to 125-mA beam current at 9 MeV, and ii) the INFN/LNL effort to build a 30-mA CW 5-MeV proton RFQ, for use in a medical neutron-irradiation (BNCT) facility.

The emphasis on front-end research and development for ADS has been on prototyping components and demonstrating beam current performance. The next phase of development will require long-term testing in order to assess and improve the reliability of front-end system components. A second thrust for R&D activities is the evaluation and control of beam halo generated in front-end systems.

Finding #8: One of the most challenging technical aspects of any ADS accelerator system, the Front-End Injector, has demonstrated performance levels that meet the requirements for industrial-scale systems, although reliability at these levels has not yet been proven.

3.3.2 Superconducting RF accelerator systems

Advantages of SRF technology in the context of a high-energy CW proton linear accelerator include:

- High accelerating gradients (~20 MV/m) which leads to lower capital and operating costs
- Low RF structure power dissipation and therefore efficient transfer of RF power to the beam
- Large aperture to reduce interception of halo particles
- Extremely low vacuum to minimize beam-gas interactions thereby reducing beam loss
- Potential for high reliability with a linac architecture in which one SC cavity is powered by a single RF source and SC cavities are maintained as online spares

Large scale SRF installation have been proven to be advantageous in operating accelerators such as CEBAF (TJNAF), SNS (Oak Ridge) and LEP (CERN). Ongoing accelerator design and construction projects that include large-scale SRF installations include FRIB, ESS, Project-X, ILC, SPIRAL-2, IFMIF, and MYRRHA.

Practical CW cavity accelerating gradient has climbed from ~5 MV/m a decade or so ago to ~20 MV/m today. Peak cavity gradients of over 35 MV/m are routinely achieved in vertical testing for electro-polished cavities, however such gradients would not be practical for CW operation with presently available materials and cryogenic technology due to cryogenic losses. The cost optimal gradient for the CW linac as a whole, taking into account capital and long term operating costs, is anticipated to lie between 15 and 20 MV/m. Optimum operating temperature is likely to be 2K or slightly below, depending on the performance of the cavities.

RF power input couplers have delivered CW power reliably in the range of ~0.5 MW to SRF cavities in storage rings such as CESR and KEK-B while klystron output windows routinely operate at the 1 MW level. RF power sources exist over a wide range of frequencies. For high-power applications, the RF plant will be a major cost driver, which would benefit from developments in RF source technology. RF costs will be dominated by the beam power requirements and will be relatively insensitive to gradient choice.

Proven cavity and cryomodule designs exist for a wide range of frequencies and particle velocities (or particle “beta” values, where $\beta=v/c$), ranging from β=0.04 to β=1. The choice of structure type, several of which are shown in figure 1, is determined by the particle velocity. Elliptical cavities are in use (at SNS) or proposed for the high-energy section of linacs, where β > 0.4. Half-wave and quarter-wave resonators have been built and tested at 4K and 2K, and are planned for use at FRIB over the velocity range 0.04 < β < 0.53. Spoke resonators have been built and tested, and are planned for projects such as Project-X (at Fermilab).

SRF linacs are complicated systems and may incur trips or downtime for many reasons. Conservative design choices for cavity gradient and coupler power would need to be adopted for ADS applications. SRF trips can occur due to quenches, vacuum events or coupler arcs. Although design choices can minimize these risks, fast recovery and restoration of beam would need to be an essential ingredient. Experience with a large scale SRF installation at CEBAF shows that cavity fields can usually be reestablished quickly (in less than one second). If a cavity cannot be restored quickly it must be safely detuned and the amplitudes and phases of neighboring systems adjusted to maintain the linac energy profile, as has been demonstrated at SNS, and is discussed below.

Finding #9: Superconducting radio-frequency accelerating structures appropriate for the acceleration of tens of MW of beam power have been designed, built and tested; some structure types are in routinely operating accelerator facilities.

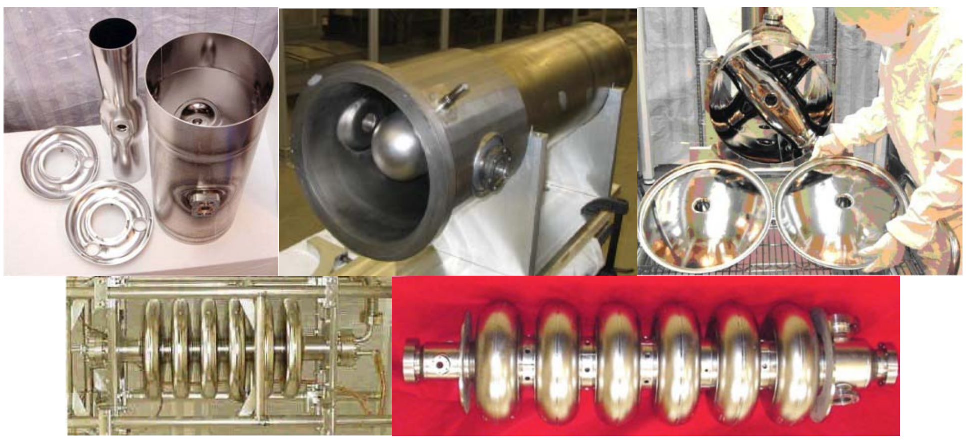

Figure 1: Superconducting accelerating structures for proton and ion beams. Structure types shown include half-wave, quarter-wave, spoke and elliptical resonators.

3.3.3 Beam dynamics and beam loss

Maintaining beam loss below 1 W/m to allow hands-on maintenance is a primary challenge in high power proton linac design and operation. For a 1 MW beam this corresponds to about a part-per-million fractional loss per meter at full energy, and for a 10 MW beam a 0.1 ppm fractional loss per meter. Predicting beam halo at these fractional levels is well beyond the present beam simulation capabilities. Primary modeling limitations include an accurate knowledge of the initial particle distribution in the full 6-D phase space, accurate modeling of the non-linear forces such as those arising from space charge, and proper treatment of longitudinal dynamics for off-energy beam particles. Presently, simulation tools agree with measurements at about the 1% level of particle fraction. Another challenge in understanding beam dynamics to very small fractional levels is the diagnostic capability for beam halo measurement, which is typically limited in both dynamic range and resolution. Present beam profile measurement resolution is at the $10^{-4} - 10^{-5}$ fractional level for a limited number of beam phase space cross-sections, which is two to three orders of magnitude greater than required levels in an ADS accelerator of 30 MW beam power.

Regarding accelerator residual radioactivation levels, the SNS linac presently operates at 1.1 MW and serves as an example of performance of a modern superconducting linac. It has residual activation levels in the range of 30-40 mRem/hr, which is about three times below the limit required for hands-on maintenance. In the SNS design, simulation codes predicted no beam loss in the superconducting linac, and the observed beam loss is not well understood. Possible explanations include longitudinal halo and intra-beam-scattering stripping of the H^- beam. Better understanding of loss mechanisms and their control is required to achieve the performance necessary in industrial-scale ADS systems, whereas the present capability in low-loss design and control is sufficient for the Demonstration mission requiring 1-2 MW beam power.

3.3.4 Reliability and beam trip rate

The ADS application has more stringent trip rate requirements than the historical high power proton accelerator experience base. However, it should be emphasized that present high power accelerators were not designed with a low trip rate requirement. In particular, accelerator facilities to serve a scientific research function do not typically invest in redundant hardware systems that would be required to achieve the high reliability performance expected for an industrial-scale installation. Nevertheless, experience at these facilities provides important guidance on the systems that require improvement in future ADS applications. Beam trip rates for the present operating high power proton accelerators (LANSCE, SNS, ISIS and PSI) are shown in Figure 2 [19]. Total annual trip counts of order 10^4 are typical, most of which last less than one minute. Present day trip frequencies with outages less than about 10 minutes are approaching recent ADS requirements. But factors of 10 to 100 reductions in the frequency of longer interruptions are needed to meet the latest ADS requirements.

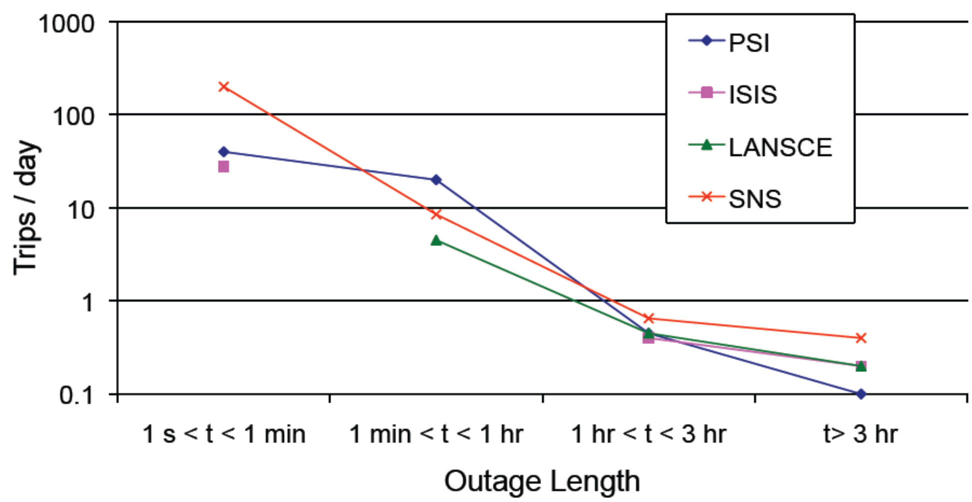

Figure 2: Beam trip frequency for operating high-power proton accelerators [19].

Detailed reliability analyses utilizing modern reliability engineering approaches have been performed [20]. The result of these studies suggest that reliability goals can be met with appropriately chosen redundancy, with adequate engineering margin, and with the incorporation of rapid fault-recovery algorithms made possible with an independently-phased superconducting linac architecture. The superconducting linac approach to production of high power beams has an inherent operational reliability advantage. Acceleration is provided by many independently-powered cavities, each of which provides only a small fraction of the total beam power. Failure of a single cavity (including its RF drive components) can be quickly "tuned around" by bringing on-line spares into operation (or adjusting already operating cavities), as has been demonstrated in practice in routine operation of the SNS [18]. The technique for SC cavity fault recovery at SNS is amenable to rapid (< 1 sec) implementation with specially designed control systems.

There are examples of extremely high-reliability achieved in large accelerator systems. The European Synchrotron Radiation Facility routinely achieves Mean-Time-Between-Failure of many days, and has recently operated for an entire month without a beam trip. The Advanced Photon Source completed 2009 with 63 beam trips recorded that year.

Finding #10: Ten to one-hundred fold improvement in long-duration beam trip rates relative to those achieved in routine operation of existing high power proton accelerators is necessary to meet industrial-scale ADS application requirements.

Finding #11: The technology available to accelerator designers and builders of today is substantially different from, and superior to, that which was utilized in early ADS studies, in particular in the design which was considered in the 1996 National Research Council report.

3.4 Required R&D for Accelerator Technology

The following summarizes R&D needs for ADS accelerator technology and systems:

3.4.1 Front-end Systems

1. Demonstrated long-term operation at high CW power levels, with assessment of reliability and availability
2. Construction and long-term operation of an ADS plant-level accelerator front end, including the low-velocity section
3. Confirmation of matching, beam quality and minimal halo growth
4. Exploration of beam scraping schemes
5. Demonstration of fast beam switching capability from a hot-spare front-end

3.4.2 Superconducting radiofrequency cavity technology

1. Demonstration, with beam, of robust SRF cavity designs for all beta values
2. Experimental verification of fast trip recovery techniques
3. Robust coupler and fast tuner technology
4. Reliable low-cost RF sources
5. Improved cleaning and processing techniques for low-frequency elliptical and spoke cavities are needed

3.4.3 Beam dynamics

1. Modeling of beam loss and halo mechanisms
2. Benchmarking of beam loss and halo models with actual accelerator performance
3. SC linac lattice design for maximum fault tolerance

3.4.4 Beam instrumentation

1. High dynamic range, high-resolution measurement of beam particle distributions.
2. High dynamic range, high-resolution measurement of beam phase-space distributions throughout the entire energy range

3.4.5 Reliability

1. Analysis of beam trip data in existing prototypical accelerators
2. Development and deployment of rapid fault-recovery schemes in SRF linacs

3. Highly-reliable accelerator architecture design

It should be emphasized that there is strong synergy between the research needs identified for ADS applications and those required for future accelerators for scientific user facilities to satisfy the demand for ever higher proton beam power.

4. Spallation Target Technology

4.1 Target Requirements

The principal mission of the spallation target is to use the energetic protons delivered by the accelerator to produce neutrons via spallation reactions with heavy nuclei. Target requirements are:

- Maximize the number of neutrons *escaping* from the target per proton incident on it.
- Accommodate high deposited power density (~1 MW/liter).
- Relative to the subcritical core, contribute in an insignificant way to the dose received by workers and the public under design basis accident scenarios.
- Operate reliably for more than six months between target replacements.
- Be capable of being replaced within a reasonable (about one week) maintenance period.

4.2 Target Technology Choices

ADS targets are generally:

- Solid target options, which consist of a solid material in the form of rods, spheres, or plates to produce the neutrons, and coolant flowing between the elements for heat removal.
- Liquid target options where a flowing liquid metal (LM) acts both as the source of neutrons and the heat removal media.

4.3 State of the Art

The state of the art for spallation target technology needed to meet the ADS mission can be correlated with the principal requirements as defined under Section 4.1, with an additional assessment related to the interface between the accelerator and target.

4.3.1 Neutronics

The target must produce the maximum number of neutrons per proton (n/p), and leak them out of the target with minimal parasitic losses or modification in energy spectrum for subsequent utilization. Achieving this objective requires trade-offs between engineering, materials, safety, operational, and cost considerations.

Tungsten, tantalum, and lead are the primary materials that have been considered, and used, for proton-driven spallation targets since the neutron yield (n/p) is proportional to the target atomic weight. While uranium and the other actinides have a higher (n/p), they introduce engineering and ES&H complexities that have generally precluded their use. The (n/p) is also proportional to the energy of the incident protons and is roughly linear over the typical range of interest for ADS (typically 0.8 – 2 GeV). The beam power needed to drive a sub-critical core whose thermal power is 0.8 GW is shown as a function of beam energy in Figure 3. Curves are shown for several representative values of core reactivity k_{src}. Note there is a broad range of acceptable beam energies for ADS applications, but in general the required beam power decreases slowly with beam energy above about 800 MeV. Other factors can influence the choice of beam energy, such as accelerator cost, neutron source spatial distribution (higher beam energy will distribute the source in the direction of the proton beam more), and peak beam current density (which sets the peak deposited power density in the spallation target and the beam window lifetime).

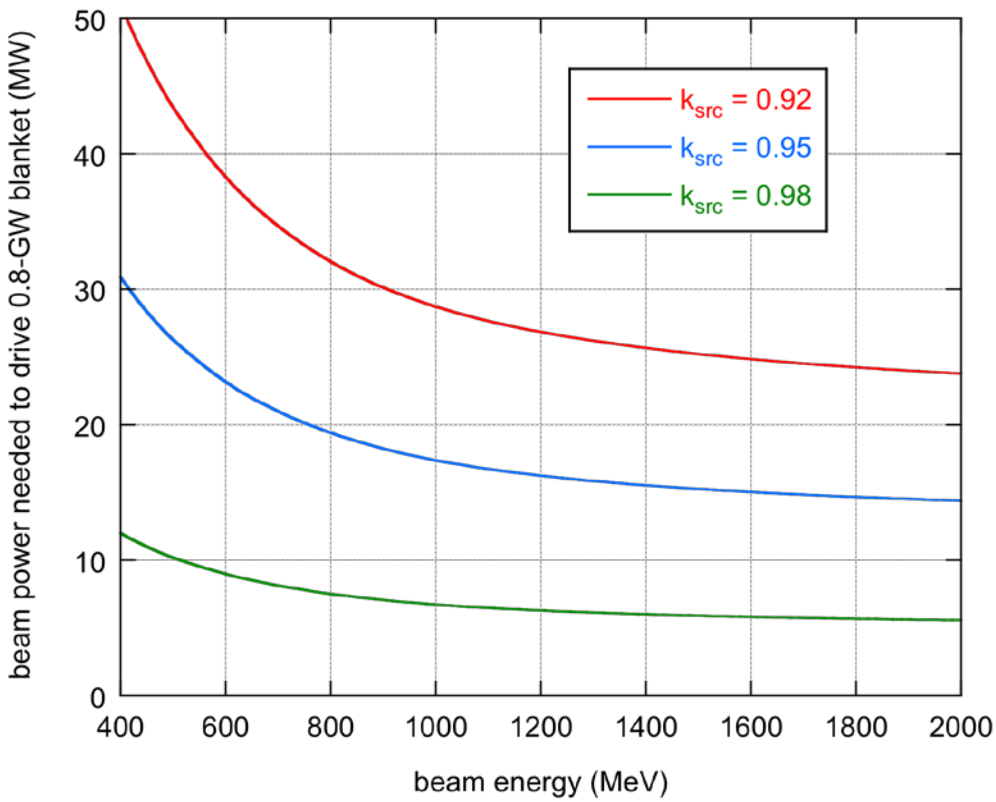

Figure 3. Beam power needed to drive a 0.8-GW ADS sub-critical core as a function of beam energy, for several values of core reactivity, k_{src} (assumes a 50-cm-diameter LBE spallation target).

4.3.2 Thermal Hydraulics

Megawatt class operation of spallation targets has been accomplished by SNS using liquid mercury (1 MW) and at the Paul Scherrer Institute (PSI) SINQ facility with water-cooled solid targets (1.2 MW) and with a LBE target (MEGAPIE, 0.8 MW). The Japanese Particle Accelerator Research Complex (J-PARC) has constructed a mercury spallation target designed for 1 MW and has operated it at up to 300 kW. A 4 MW mercury spallation target was designed for the EURISOL study and a full scale mercury hydraulic loop constructed and tested at the Institute of Physics of the University of Latvia. Spallation targets for ADS application well above 1 MW will likely use heavy liquid metal cooling to achieve compact designs. The only example of lead or LBE cooling for high power is the Russian LBE submarine reactors which were designed for approximately 150 MW. In general it appears that the primary thermal hydraulic performance can be reasonably predicted for liquid metal targets with a combination of empirical testing and CFD analysis. Significant design development and testing will likely be needed to qualify the target and all the major loop components (pumps, heat exchangers, valves, sensors, etc.) for use in an ADS facility. Design considerations include material compatibility, safety, radiation damage, remote handling and required reliability.

Operating spallation target facilities have all used one or more metal windows to separate the beam vacuum from the target material or environment. High heating and thermal stress in the window generally limits the thickness and peak current density. Options for reducing the peak current density while maintaining a small beam spot is important for window design. Methods for obtaining nearly flat profiles by rastering the beam (moving a small beam spot rapidly over a specified footprint) have been proposed and analyzed in the past. Significantly higher current densities appear to be achievable in windowless liquid metal designs. This is still in the R&D phase, but promising results have been shown in tests for the MYRRHA and EURISOL projects and in liquid lithium tests done by Argonne National Laboratory with electron beam heating. Testing for ADS systems would be needed to show that stable flow conditions can be maintained with high beam heating and that adequate vacuum can be maintained for the beam. Beam control diagnostics would have to be demonstrated and safety considerations may require testing for off normal conditions.

Finding #12: Spallation target technology has been demonstrated at the 1-MW level, sufficient to meet the "Transmutation Demonstration" mission.

4.3.3 Safety

Ensuring the safe operation of the target during normal and off-normal conditions is critical to the viability and attractiveness of ADS for proposed applications. The key issues that need to be addressed under all postulated normal and transient/accident conditions include:

- **ensure adequate cooling of the target**: the proton and neutron fields, and the spallation process create radioactive products that produce heat as they decay. Therefore, heat removal must consider removal of heat during operation and anticipated transients, as well as when the proton beam has been turned off.
- **maintain the structural integrity of the target system:** so as to not negatively impact the facility operations and not impact the reactivity of the sub-critical blanket
- **manage/contain the radioactive inventory:** radioactive isotopes will be produced in the spallation target. While the bulk of these isotopes will be created in the neutron-generating target in the case of solid targets and the target design will address their retention under all anticipated scenarios, activation of the coolant and the structures must be considered for normal and off-normal operations, elements of the coolant circuit, and target handling. In the case of LBE, the production of Po-210, an alpha emitter with a 138-day half-life, introduces potentially significant dose to the public and workers that must be adequately addressed through safety analysis. There must be provision to physically isolate the target/blanket system so as to retain and prevent the release of radioactive material, and prevent contamination of the accelerator and beam conditioning components in case of damage.
- **accommodate accelerator induced transients/upsets:** the target must be designed to accommodate accelerator trips, start-up transients, and potential malfunctions in the beam raster system if it is employed. Also, some capacity to adjust the power of the beam may be built in to the accelerator to compensate for changes in the reactivity of a subcritical blanket so as to maintain a constant system power level. Potential malfunctions of this capability must also be considered to prevent damage.

4.3.4 Target Lifetime

The target structure material has to function under harsh operating conditions induced from the direct exposure to the proton beam. The nuclear heating in the beam window requires thin structure to limit the maximum temperature of the beam window material. This limit is set based on the irradiated structural material properties for accommodating the induced stresses. In addition, the mechanical properties are degraded due to the protons' and the produced neutrons' interactions with the structure materials, which result in a high atomic displacement values and the generation of a large amount of helium and hydrogen. These nuclear responses must be considered in the design process of the target structure.

As the target operates, radiation-induced degradation of the mechanical properties continues, which results in reduced allowable stresses for the structural materials. The target structure must be replaced once the operating stresses approach the allowable stresses. In addition, chemical conditions and the speed of the coolant material define the corrosion and the erosion of the target structure, which reduce the effective thickness of the structure material for accommodating the operating stresses. For example, for LBE coolant operating above 350 °C the oxygen content has to be controlled within a specific range to avoid severe corrosion. Also, liquid metal coolants can cause embrittlement, which reduces the tensile ductility and causes brittle fracture. Proton beam interruptions result in cyclic thermal stresses, which can produce thermal fatigue and limit the target lifetime. The irradiated structure materials can accommodate a limited number of these interruptions. The allowable number of cycles is a function of the temperature variation, radiation fluence, and the material alloy properties.

The current worldwide engineering experience and database for designing and operating ADS targets are very limited. The irradiated structure design criteria for analyzing the calculated stresses are not approved by any regulatory body around the world, however some effort is under way. The Accelerator Production of Tritium (APT) Project and the International Thermonuclear Experimental Reactor (ITER) developed structure design criteria for the nuclear components and efforts are under way to review and include these criteria in the ASME code. The current state of the art is adequate to perform the design process but design validation and an improved materials database are required.

4.3.5 Maintenance & Remote Handling

Remote handling and maintenance will be needed for ADS targets and liquid metal loop components due to high activation levels. An example of current technology is the SNS target cell which was designed to accomplish all operations within the cell fully remotely and has successfully replaced activated targets. The principal systems are a bridge mounted dual arm servo-manipulator, a bridge mounted crane and through the wall master slave manipulators. These are controlled by operators using in-cell cameras and shielding widows. J-PARC uses similar systems for target maintenance. One unexpected operational finding seen at both facilities was that the radiation dose levels on the piping after operation increased by about a factor of two after draining the mercury. Gamma-spectra data at J-PARC showed that this was due to spallation products such as ^{188}Ir and ^{185}Os left on the wetted surfaces. ADS maintenance will be challenging because of the likely need to operate within an opaque liquid at 250 °C or higher within LBE or lead. Extensive development and testing of equipment and sensors such as ultrasonic imaging will be needed. Overall facility layouts will need to incorporate access requirements for remote handling. This may be particularly challenging for ADS systems where most concepts to date assume vertical beam insertion from above into the center of the sub-critical core, which is an area that will likely also contain fuel handling equipment. Mockup testing of all major remote handling operations should be conducted.

4.3.6 Accelerator-Target Interface

Beam spot profile (rastering or expansion/flattening) A beam spot with uniform current density is desirable in order to minimize the peak deposited power density within the spallation target and to maximize target lifetime. The optimal solution is probably a combination of high frequency beam rastering and magnification by beamline magnets. Candidate designs for the rastering systems have been studied at LANL and JLab. For a fixed beam spot size, rastering offers a reduction in peak current density by as much as a factor of two over conventional quadrupole beam expansion that typically yield Gaussian profiles.

Diagnostics (target front face imaging and other diagnostics) In addition to conventional beam monitoring devices such as beam profile, halo and position monitors, optical or thermal imaging of the spallation target front face is a powerful diagnostic capability that has seen recent advances at the present generation MW-scale spallation neutron sources (SNS, J-PARC, and PSI). If a rastering system is employed, B-dot loops in the raster magnets and I-dot loops in the magnet power supplies offer multiple and diverse signals for quickly tripping the beam in case of raster system failures.

Need for equipment protection during off-normal events Thermal shock and associated fatigue of the target components, especially the containment materials of the liquid target and fuel assemblies must be minimized. Hence, fail-safe and fast-reacting beam trip diagnostics and controls are absolutely essential. Thermophysical simulations will determine the permissible beam restart scenario, i.e. how quickly the beam power can be ramped back to full power. A very reliable, robust control system is required to ensure smooth beam power ramp-up. Again, much important progress has been made in this field at the present generation of MW-scale accelerators.

4.4 R&D Required to Meet ADS Missions

The operation of MW-class liquid metal targets in the last few years is a strong indicator that, with appropriate design development and testing, spallation targets can meet the ADS mission. Scaling from existing 1-MW operation to 3 to 10 MW would be an appropriate next step (the European Spallation Source Project proposes to construct and operate a 5-MW spallation target). After successful operation at this power level, the next step would be to build and operate a spallation target for tens of MW, sufficient to drive an industrial scale transmuter. Following is the R&D needed to step up from current power levels.

4.4.1 Liquid Metal Targets

1. Oxygen control in an LBE environment. The successful MEGAPIE experiment operated in a temperature range where oxygen control was not needed to limit container corrosion. But targets for the ADS mission will likely need to employ oxygen control. A number of out-of-beam LBE loops with oxygen control exist today that can be used to further develop appropriate operating conditions that limit corrosion of steels in contact with LBE. This testing should be augmented by one or more long-term in-beam tests.
2. Polonium release from LBE. To support safety analyses, measure Po release fractions from LBE as a function of LBE temperature and concentration of trace contaminants.
3. LBE cleanup chemistry. To limit corrosion of steels in contact with LBE, develop LBE cleanup chemistry techniques.
4. Plate out of spallation products throughout the circulating LM system (piping, heat exchanger(s), filters) is likely with an LM target. The impact on personnel dose and ways to ensure RAMI (Reliability, Availability, Maintainability and Inspectability) and ways to mitigate adverse consequences should be explored.
5. Develop criteria, verified by testing, required for safe and reliable operation of a windowless (LBE) liquid target.

4.4.2 Solid Targets

While LM targets have several benefits in high power density compact applications, the potential of solid targets to satisfy mission requirements should not be ignored. The principal benefit of a solid target is that the radioactive spallation products are generally confined to the solid target material and are localized in the target proper (barring catastrophic failure). The radioactivity in the primary coolant will depend on the coolant utilized and the design of the primary coolant loop, but should be significantly less of an issue than for LM targets.

Solid target options should be evaluated and their performance and ES&H characteristics compared to those of LM targets. Carrying along a solid target option at the early stages of ADS conceptual design, if warranted by the comparative studies suggested above can reduce programmatic risk.

4.4.3 Independent of Target Type

1. Materials irradiations. Extend the irradiated materials database to include ADS environmental conditions (elevated temperature, contact with liquid metal, fatigue) and structural materials relevant to ADS applications. Incorporate the database into ASME and other code standards.
2. Subscale heat transfer and flow testing at operating temperatures.
3. Full scale testing at operating temperatures.
4. Off normal testing of safety systems
    a. Leak containment – thermal shock on structures
    b. Decay heat removal – natural convection testing may be needed
5. Component testing under operating and off normal conditions.
6. Remote handling development testing for components.
7. Develop higher frequency (10-100 kHz), redundant/fail-safe raster power supplies and magnets with telescopic image magnification (2-4x) for uniform circular beam spots.
8. Develop real-time, non-destructive beam imaging for 10-100 mA – e.g. residual gas fluorescence imaging.
9. Develop through large-scale simulations detailed criteria for beam-trip recovery scenarios to minimize damage to liquid target and solid or liquid fuel containment vessels.
10. Examine issues associated with integral cooling of the target and the sub-critical blanket via a single loop.
11. Address interface issues of the target with the accelerator and sub-critical blanket

Finding #13: With appropriate scaling at each step along a technology demonstration path, there are no obstacles foreseen that would preclude the deployment of spallation targets at a power level (10 to 30 MW) needed to meet the application of ADS at an industrial scale.

5. Technology Assessment

If a commitment were to be made to develop ADS technology in order to realize its potential in a future US deployment strategy, technical readiness would need to be established through a development program for the various accelerator and spallation target components, sub-systems and systems. The key technologies and issues for the Accelerator-Target system are displayed in Figure 4.

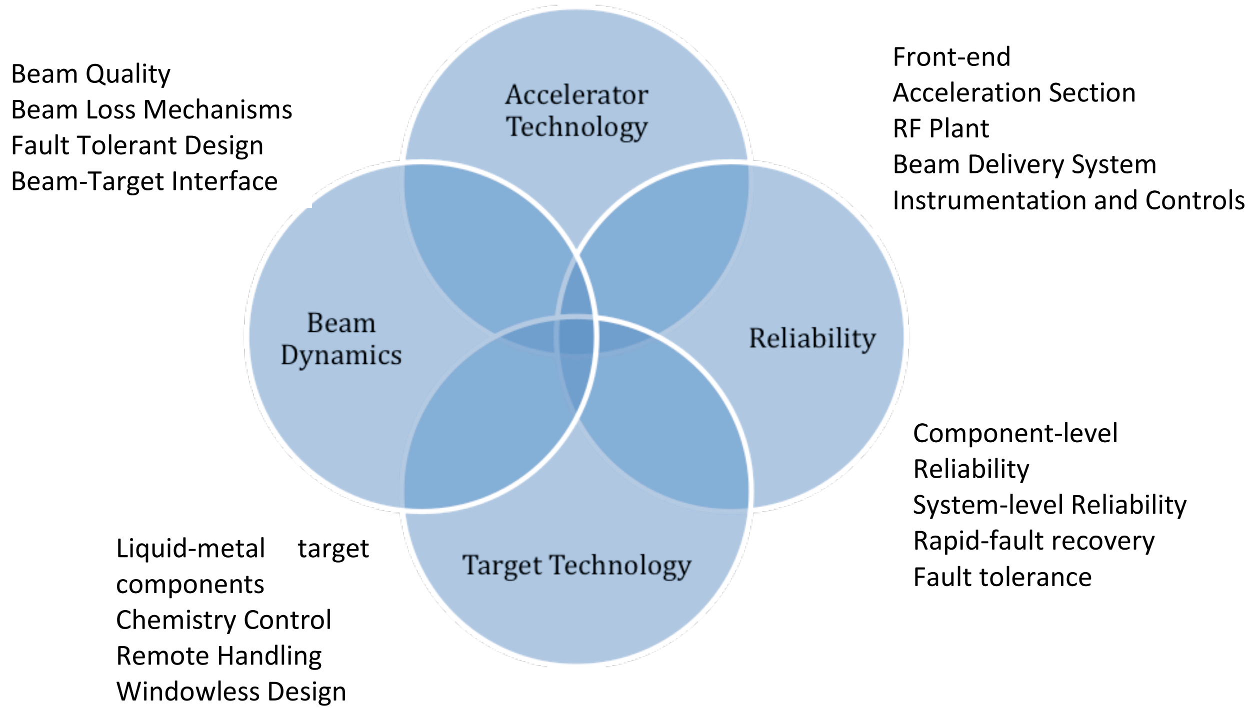

Figure 4: Key technologies and issues for the Accelerator-Target system. Many of the most challenging technical issues are inter-related.

The required level of technology development depends on the mission under consideration. The following summarizes technology readiness and highlights areas where further development activities are required in order to establish readiness for coupling a MW-class accelerator to a subcritical reactor in support of the *Transmutation Demonstration* mission.

Front-end systems: beam current and beam quality performance have been achieved, but

- Reliability limitations need better understanding

Accelerating System: accelerating structure development and performance are ready (although there remains the potential for cost reduction with improved gradient and quality factor), but

- Fast cavity trip recovery needs development
- Low energy linac module (source+RFQ+low-beta section) requires prototyping

RF Plant: RF power sources are available, but cost reduction and AC to RF power efficiency is a priority
Beam Delivery: beam delivery and raster systems are demonstrated and in operation
Target System: successful operation of megawatt class liquid metal and solid targets has been demonstrated; further development is required to

- Demonstrate LBE corrosion control at prototypic operating conditions
- Verify LBE pressure drops, flow rates and structural erosion through out-of-beam testing
- Demonstrate technology to respond rapidly to loss of beam heating when beam is tripped
- Mock-up remote handling testing of system serviceability
- Expand irradiated materials database
- Test windowless design for high power operation
- Compare solid target designs vs. liquid metal targets

Instrumentation and Control: beam instrumentation is ready, but

- Accelerator-target interface instrumentation requires development

Beam Dynamics: understanding of emittance growth/halo/beam loss is sufficient, provided adequate margin and conservatism are preserved in the design

System Reliability:

- Rapid SCL cavity/magnet fault recovery requires development and demonstration
- Bottoms-up reliability engineering approach is required
- Redundant front-end concept requires study and beam quality preservation demonstration

The following summarizes technology readiness and highlights areas where further development activities are required in order to establish readiness for a prototype plant for *Industrial Scale Transmutation*.

Front-end: beam current performance has been demonstrated, but

- Reliability limitations need better understanding
- Long-term high-reliability operation of the front-end system requires demonstration

Accelerating System: accelerating structure performance is ready (although there remains the potential for cost reduction with improved gradient and quality factor), but

- prototype cryomodules of each type need demonstration at design fields and validation of acceptable trip-rates
- low energy linac module (source+RFQ+low-beta section) requires demonstration of long-term high-reliability operation
- high-power, robust RF input couplers are ready, but there remains the potential for cost-savings

RF Plant: RF power sources are available, but cost reduction and AC to RF power efficiency is a priority, but

- reliability engineering of high power RF components is required
- high-reliability operation of RF/Cryomodule units requires demonstration

Beam Delivery: beam delivery and raster systems are demonstrated and in operation

Target System:

- Develop, prototype and test components for > 10 MW target systems
- Identify and develop data and methods for assessments and licensing
- Develop windowless systems for higher power
- Develop online chemistry control for liquid metal requires development

Instrumentation and Control;

- Develop instrumentation for greater dynamic range and/or sensitivity for improved measurement of beam profiles and distributions

Beam Dynamics

- Understanding of emittance growth/halo/beam loss needs to be improved through measurement, theory, simulation, benchmarking
- Lattice studies incorporating dedicated scraper/collimation systems are needed
- Fault-tolerant linac lattice and beam delivery design is needed

System Reliability

- Rapid SCL fault recovery requires development and demonstration
- Bottoms-up reliability engineering approach is required

Technology readiness for the *Power Production* mission requires further development (beyond that required for the *Transmutation* mission) focused on overall system reliability.

These findings are summarized in the following Technology Readiness Assessment table, in which green color-coding indicates "ready", yellow indicates "may be ready, but demonstration or further analysis is required", and red indicates "more development is required". For meeting near-term needs of a *Transmutation Demonstration* facility, the basic technology is already in-hand; development is required for increasing overall system reliability. For *Industrial-Scale Transmutation*, many of the key technologies are in-hand, including front-end systems and accelerating systems, but demonstration of other components, improved beam quality and halo control, and demonstration of highly-reliable sub-systems is required. For power production, the lessons learned of the previous generation of ADS facilities is required to further improve the reliability at the component, sub-system and overall system level.

Table 3: ADS technology readiness assessment. The color-coding is explained in the text.

		Transmutation Demonstration	Industrial-Scale Transmutation	Power Generation
Front-End System	Performance			
	Reliability			
Accelerating System	RF Structure Development and Performance			
	Linac Cost Optimization			
	Reliability			
RF Plant	Performance			
	Cost Optimization			
	Reliability			
Beam Delivery	Performance			
Target Systems	Performance			
	Reliability			
Instrumentation and Control	Performance			
Beam Dynamics	Emittance/halo growth/beamloss			
	Lattice design			
Reliability	Rapid SCL Fault Recovery			
	System Reliability Engineering Analysis			

Finding #14: Technology is sufficiently well developed to meet the requirements of an ADS demonstration facility; some development is required for demonstrating and increasing overall system reliability.

Finding #15: For *Industrial-Scale Transmutation* requiring tens of MW of beam power many of the key technologies have been demonstrated, including front-end systems and accelerating systems, but demonstration of other components, improved beam quality and halo control, and demonstration of highly-reliable sub-systems is required.

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