AVAILABILITY ANALYSIS FOR THE 30-MW PROTON LINAC OF THE JAEA-ADS PROJECT

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Abstract

Japan Atomic Energy Agency (JAEA) is designing a 30-MW proton linear accelerator (linac) as one of the fundamental components for its accelerator-driven subcritical system (ADS) proposal. ADS accelerators demand extremely high reliability and availability to avoid thermal stress in the subcritical reactor structures. Thus, reliability and availability assessments of the accelerator are mandatory to detect weakness in the lattice designed and evaluate redundancy configurations to fulfill the demanded operation. This study applied the Reliability Block Diagrams (RBD) method to calculate the Medium Time Between Failures (MTBF) for different linac configurations: all the linac's elements in a series configuration and a combination of hot-standby for the low-energy section of the linac and *k-out-of-n* redundancy for the high-energy part. The estimation considered the detailed arrangement of the cavities and magnets that compose the linac lattice. In this report, we describe the reliability model of the JAEA-ADS linac, report the MTBF results, and point out the potential route toward operating with the required availability.

INTRODUCTION

The Japan Atomic Energy Agency (JAEA) is working on the design of a 30-MW CW proton linear accelerator (linac) for the accelerator-driven subcritical system (ADS) proposal [1]. Figure 1 displays a simple schematic of the JAEA-ADS facility. Support systems are all the infrastructure required to operate the linac: electrical power grids and cryogenic plant, among others. The JAEA-ADS linac will accelerate a 20 mA proton beam to a final energy of 1.5 GeV. Then, the beam transport to the target (BTT) will carry from the end of the linac to the spallation target inside the 800-MWth thermal power subcritical reactor.

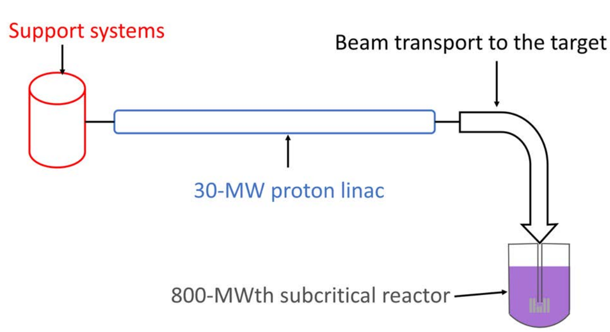

Figure 1: JAEA-ADS design.

Table 1 summarizes the most relevant parameters of the JAEA-ADS linac. Reliability is the priority requirement for the ADS to avoid thermal stress in the subcritical reactor structures due to beam trips. The beam trip analysis for the JAEA-ADS facility estimates the Medium time between failure (MTBF) is about 172 h, based on beam trips longer than 5 minutes [2]. Such reliability is beyond the current linac performance; thus, the JAEA-ADS linac adopted a reliability-oriented design [3].

Table 1: Main Characteristics of the JAEA-ADS Accelerator

Parameter	
Particle	Proton
Beam current (mA)	20
Beam energy (GeV)	1.5
Duty factor (%)	100 (cw)
MTBF (h)	>172

Figure 2 shows the JAEA-ADS linac baseline. It is composed of a normal conducting part and a superconducting section. Most of the energy gain is provided by the superconducting region that comprises three different types of SRF cavities operating at different frequencies: Half-Wave Resonator (HWR) operates at 162 MHz, Single Spoke Resonator (SSR), at 324 MHz, and five-cell Elliptical Resonator (EllipR), at 648 MHz. Additionally, the SSR and EllipR sections have two different SRF cavity models, each of them optimized at a different geometrical beta β_g to achieve high acceleration [4].

After obtaining a robust beam optics design, we implemented fast beam recovery schemes based in hot standby and local compensation based on *k-out-of-n* to reduce the beamdown time due to the beam trips [5]. This scheme is known as fault-tolerance configuration.

This work assessed the reliability of the full JAEA-ADS facility. Furthermore, it showed that the fault-tolerance schemes for the linac satisfied the requirements of MTBF for the JAEA-ADS proposal.

METHODOLOGY

This analysis was based on the reliability engineering works [6–8] and high-intensity linac reliability studies [9–12]. The calculations concentrated on evaluating the facility's reliability during the useful life period of the system. Figure 3 shows the common failure rate evolution of the system, the so-called bath-tub curve. At the useful life period, the failure rate (λ) is constant.

λ is expressed as:

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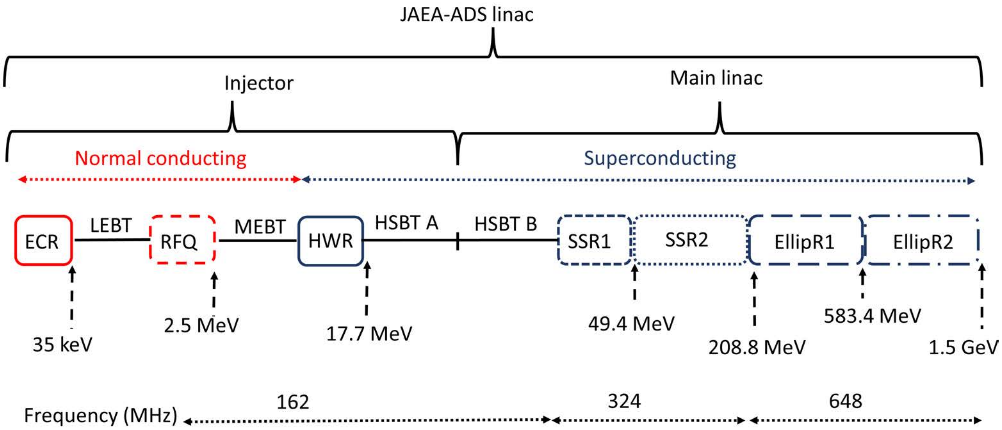

Figure 2: JAEA-ADS linac configuration.

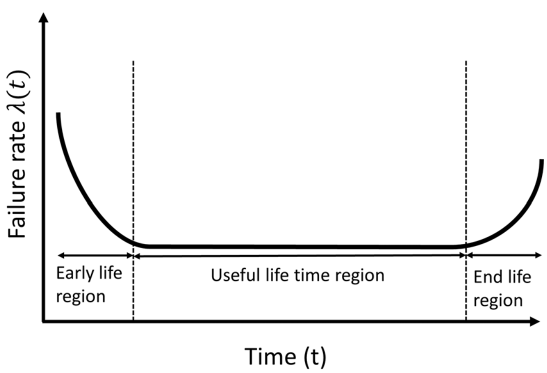

Figure 3: Failure rate evolution of a system.

$$\lambda = \frac{1}{\text{MTBF}}. \tag{1}$$

Availability (A) is the common figure of merit to evaluate the reliability of the linacs. A is the probability that a system is properly operating when it is required, and it has the following simple steady-state representation:

$$A = \frac{\text{MTBF}}{\text{MTBF+MTTR}}, \tag{2}$$

where MTTR is the medium time to repair.

Reliability analysis was performed using reliability block diagrams (RBD). The RBD approach divides a system into individual blocks where reliability parameters are estimated. Figure 4 shows the different configurations of the elements that were considered for the JAEA-ADS linac. In series connect: if one of the sections fails, the full system is down. For the hot standby, part of the system is duplicated, with one part the principal operator and the other as offline-powered equipment ready to operate in case of a failure in the major structure. The *k-out-of-n* configuration states that a system composed of n elements needs at least k of its components to operate.

For each of the connections, the equations to compute the MTBF and A for repairable systems are provided.

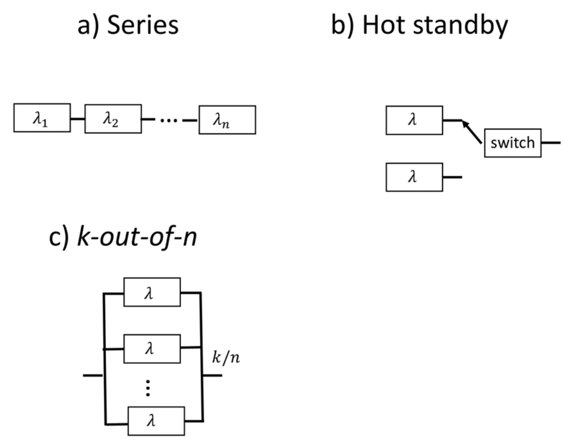

Figure 4: System connections: series (a), hot standby (b), and *k-out-of-n* (c).

Series:

$$\text{MTBF}_{\text{Series}} = \frac{1}{\sum_i \lambda_i}, \tag{3}$$

$$\text{A}_{\text{Series}} = \prod \text{A}_i, \tag{4}$$

where λ_i and A_i are the failure rate and availability of the i element, respectively.

Hot standby:

$$\text{MTBF}_{\text{hot standby}} = \frac{3\lambda + \mu}{2\lambda^2}, \tag{5}$$

where $\mu = 1/\text{MTTR}$.

$$\text{A}_{\text{hot standby}} = \frac{2B + B^2}{1 + 2B + B^2}, \tag{6}$$

where the B = MTBF/MTTR.

k-out-of-n:

$$\text{MTBF}_{k-out-of-n} = \frac{(k-1)!\,\mu^{n-k}}{n!\,\lambda^{n-k+1}}. \tag{7}$$

$$A_{k-out-of-n} = \sum_{i=k}^{n} \frac{n!}{i!(n-i)!} A^i (1-A)^{n-i}, \qquad (8)$$

where the n elements have the same availability A.

This study assumed that each element is completely independent, except for the relationship indicated in the RBD. The calculations were done by implementing the formulas in a python [13] script, which results had a good agreement with a free reliability software [14] and other reliability studies [9, 10] .

RESULTS

The MTBF of the JAEA-ADS facility was computed as a series connection of the support systems, JAEA-ADS linac, and BTT, as shown in Fig. 1. This was done to evaluate different configurations applied to the linac. Table 2 shows the data input used in this analysis. The values are based on availability studies on high-intensity linac facilities [9–12]. Table 2 has two types of SRF cavity packages: low-β and high-β. low-β value was obtained from the PIP-II analysis for the HWR cavities [10]. In our study, the low-β are also used for SSRs cavities. The high-β corresponds to the elliptical cavities and uses the data from SNS [11]. In addition, two types of quadrupoles were employed: one to operate in the normal environment of the linac and the other to operate in a high radiation environment, BTT.

Table 2: Reliability Values of the Components Use for the RBD Calculations

System/package	MTBF (h)	MTTR (h)
Support systems	1.8×10^3	46
ECR package	1×10^3	2
LEBT package	6.7×10^3	5.4
Buncher package	1.3×10^4	9
Low-β SRF cavity package	2.9×10^4	7.7
High-β SRF cavity package	1.2×10^4	5.6
Solenoid package	8.3×10^4	67.8
Quadrupole package	3.1×10^4	2.4
Quadrupole package in BTT	7.1×10^4	44.6
Dipole package in BTT	7.1×10^4	24
Vacuum system	4×10^4	4
Steering system	8.3×10^4	2
Control system	5×10^4	1.2
Local cryogenic system	5×10^5	2

For support systems, Tables 2 and 4 reported the MTBF, MTTR, and availability were used in this analysis. The reliability for the BTT was computed as a series configuration of the elements that composed it. Table 3 presents information on the configuration of BTT [15, 16]. The BTT section was modeled using the configuration presented in Fig. 5. Each transport line contains one auxiliary system and does not have local cryogenics. The MTBF and availability were computed by using input data of Table 2, and their values are reported in Table 4.

Table 3: Configuration of the beam transport lines for the JAEA-ADS design. The notation for representing the elements is B = Buncher cavity, D = Dipole, S = Solenoid, and Q = Quadrupole.

Section	Q	S	D	B
MEBT	6	0	0	2
HSBT A (series)	0	0	0	0
HSBT B (series)	0	1	0	0
HSBT A (fault-tolerance)	7	0	1	1
HSBT B (fault-tolerance)	6	0	0	2
BTT	11	0	2	0

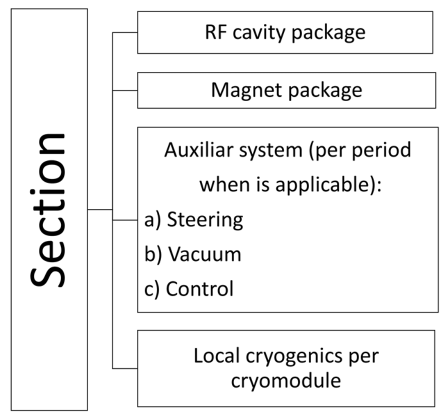

Figure 5: Block diagram for the JAEA-ADS linac and BTT.

The analysis focussed on the reliability of the JAEA-ADS linac. Figure 6 depicts the two schemes for the JAEA-ADS facility considered in this analysis: series and fault-tolerance. The fault-tolerance scheme was developed from fast beam recovery studies for the JAEA-ADS linac to achieve high reliability [5]. Fault-tolerance consisted of the use of hot-standby redundancy from the ECR to the HWR section, the so-called injector, and local compensation based on *k-out-of-n* redundancies for the rest of the linac, i.e., from the SSR1 section to the end of the linac.

Table 4: Summary of the MTBF and Availability of the Support Systems and the BTT for the JAEA-ADS Facility

Section	MTBF (h)	steady state availability (%)
Support systems	1881.2	97.6
BTT	5100	99.1

This study compared the MTBF for series against fault tolerance schemes for the JAEA-ADS linac to evaluate which configuration is most suitable for the ADS project. The MTBF of the section will be the contribution of the RF cavities, magnets, auxiliary systems per period, and local cryogenics connected in series, shown in Fig. 5. It is noteworthy that the RF cavity and magnet packages considered

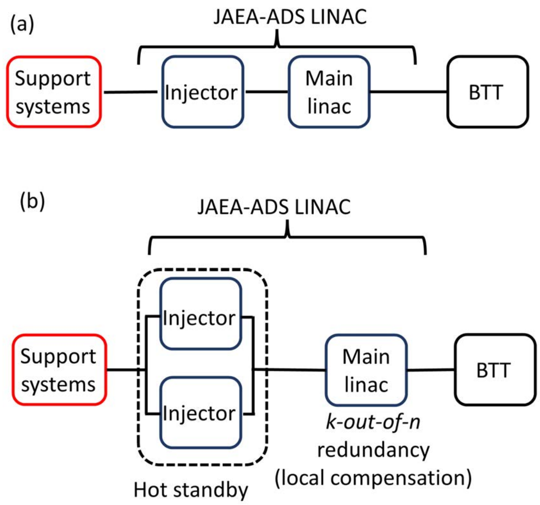

Figure 6: Diagram for the JAEA-ADS accelerator facility. Subplot (a) shows the a series connection configuration. Subplot (b) is the the fault-tolerance configuration which consist in hot-standby in the injector part and *k-out-of-n* redundancy configuration for the main linac.

the entire assembly, such as power supplies and instrumentation. Tables 3 and 5 show the configuration of each section that composes the JAEA-ADS linac.

Table 5: Lattice configuration in the superconducting linac. The notation used for the layout is C = SRF cavity, S = Solenoid, and Q = Quadrupole.

Section	**Layout**	**Baseline**	
		Cavities/ Magnets	**Periods/ Cryomodules**
HWR	S-C	25/25	25/3
SRR1	S-C^2	66/33	33/33
SSR2	S-C^3	72/24	24/24
EllipR1	Q^2-C^3	60/42	21/21
EllipR2	Q^2-C^5	70/28	14/14

Table 3 presents two beam transport line designs from the HWR to the SSR1 section, HSBT. In addition, HSBT is divided into two regions: HSBT A and B. HSBT A is the part of the transport line that is duplicated when the hot standby scheme is applied. On the contrary, HSBT B is the part that is common for both injectors. When a series configuration is considered, HSBT is only HSBT B that is composed of one solenoid, as reported in the reference design [4]. Fast beam recovery studies showed we could simultaneously compensate for the failure of all the SRF cavities or magnets that composed a period from the SSR1 to EllipR2 sections. The *k-out-of-n* redundancy is only applied to the RF cavity and magnet packages. For example, in SSR1, a period comprises one solenoid and two SSR cavities. The total amount of solenoids and cavities is 33 and 66, respectively. Thus, the *k-out-of-n* redundancy indicated that the SSR1 section could operate if *64-out-of-66* cavities were operational. Similar to the solenoids, *32-out-of-33* was required to work.

Table 6: MTBF for the Different Section of the JAEA-ADS Linac Baseline

Section	**MTBF (h)**	
	Series	**fault-tolerance**
Injector	2.3×10^2	3.4×10^3
HSBT B	8.3×10^4	4.2×10^3
SRR1	2.4×10^2	6.7×10^2
SSR2	2.6×10^2	9.2×10^2
EllipR1	1.4×10^2	1.1×10^3
EllipR2	1.4×10^2	1.6×10^3
Whole linac	3.8×10^1	2.1×10^2

Table 6 summarizes the MTBF for series and fault-tolerance configurations for the baseline design of the JAEA-ADS linac. MTBF is greater for the fault-tolerance case than the series one, except for the HSBT B section. However, this is because the HSBT B for series configuration comprised only one solenoid, as shown in Table 3. In series configuration, the MTBF was decreased when the number of elements increased. In the case of fault tolerance, the MTBF mainly depended on the number of elements that were compensated simultaneously: as the number of compensated components increased, the MTBF increased. The MTBF of only the JAEA-ADS linac is 38 and 210 h for series and fault-tolerance, respectively.

Table 7: Summary of the MTBF and Availability of the JAEA-ADS Facility for the Different Configurations

Configuration	**MTBF (h)**	**steady state availability (%)**
Series	36.9	82.6
Fault-tolerance	184.1	95.9

Table 7 reports the MTBF and steady-state availability for the JAEA-ADS installation, considering the contribution of the support systems, the JAEA-ADS linac, and the BTT. The MTBF for the series scheme was about 37 h, but the fault tolerance was 184 h, which is higher than the required MTBF.

CONCLUSIONS

This work assessed the MTBF and the steady state availability of the JAEA-ADS facility, for its useful life period, by using the reliability block diagram method. The analysis separated the contributions into three parts: support systems, JAEA-ADS linac, and beam transport to the target. This study focussed on the contribution of the JAEA-ADS linac baseline design considering two configurations: series and fault-tolerance, which comprise hot standby by the injector part and *k-out-of-n* redundancy for the main linac. The calculations used data from other high-intensity accelerator facilities and a detailed configuration of the elements that composed the JAEA-ADS linac lattice.

Fault-tolerance scheme exhibited high-reliability performance by increasing the MTBF almost six times regarding the value achieved by the series configuration. As a result, the MTBF of 184 h satisfies the requirement over 172 h. This result shows that fast beam recovery schemes for the linac allowed to fulfill the requirements of MTBF for the JAEA-ADS design. In future work, a more robust model will be developed to provide a more accurate assessment of the reliability.

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REFERENCES

[1] T. Sugawara *et al.*, "Research and Development Activities for Accelerator-Driven System in Jaea", *Prog. Nucl. Energy*, vol. 106, p. 27, Feb. 2018. `doi:10.1016/j.pnucene.2018.02.007`

[2] H. Takei *et al.*, "Estimation of acceptable beam-trip frequencies of accelerators for accelerator-driven systems and comparison with existing performance data", *J. Nucl. Sci. Techol.*, vol. 49, p. 384, Sep. 2012. `doi:10.1088/00223131.2012.669239`

[3] J.L. Biarrotte, "Reliability and fault tolerance in the European ADS project", CERN, Geneva, Switzerland, Rep. CERN-2013-001.481, June 2011.

[4] B. Yee-Rendon *et al.*, "Design and beam dynamic studies of a 30-MW superconducting linac for an accelerator-driven subcritical system", *Phys. Rev. Accel. Beams*, vol. 24, p. 120101, Dec. 2021. `doi:10.1103/PhysRevAccelBeams.24.120101`

[5] B. Yee-Rendon *et al.*, "Beam dynamics studies for fast beam trip recovery of the Japan Atomic Energy Agency accelerator-driven subcritical system", *Phys. Rev. Accel. Beams*, vol. 25, p. 080101, Aug. 2022. `doi:10.1103/PhysRevAccelBeams.25.080101`

[6] Military Handbook: Electronic Reliability Design Handbook, MILHDBK-338B, Department of Defense of USA, Washington, USA, Oct. 1998, pp 5-31. `https://www.navsea.navy.mil/Portals/103/Documents/NSWC_Crane/SD-18/Test\%20Methods/MILHDBK338B.pdf`

[7] M. A. McGregor, "Approximation formulas for reliability with repair", *IEE Transaction on Reliability*, vol. R-14, p. 64, Dec. 1963. `doi:10.1109/TR.1963.5218229.`

[8] C. M. Piaszcyk, "Reliability, availability & maintainability", JAERI, tokai, Japan, Rep. JAEARI-Conf 96-012, May 1996.

[9] L. Burgazzi and P. Pierini, "Reliability studies of a high-power accelerator for accelerator-driven system applications for nuclear waste transmutation", *Reliab. Eng. Syst. Saf.*, vol. 92, p. 449, Dec. 2006. `doi.org/10.1016/j.ress.2005.12.008`

[10] A. Saini *et al.*, "Assessment of operational availability for the PIP-II Superconducting Radio Frequency linear accelerator facility", *Nucl. Instrum. Methods Phys. Res. A.*, vol. 988, p. 164874, Nov. 2020. `doi.org/10.1016/j.nima.2020.164874`

[11] M. J. Haire and J. C. Schryver,"Computation of Normal Conducting and Superconducting Linear Accelerator (Linac) Availabilities", ORNL, USA, Rep. ORNL/TM-2000/93, Dec. 1999.

[12] JAERI, "IFMIF-KEP International fusion materials irradiation facility key element technology phase report", JAERI, Tokai, Japan, Rep. JAERI-Tech 2003-005, March 2003.

[13] Python, `https://www.python.org/`

[14] Reliability Analytics Tookit, `https://reliabilityanalyticstoolkit.appspot.com/`

[15] B. Yee-Rendon *et al.*, "Beam physics design of a 30-MW beam transport to the target for an accelerator-driven subcritical system", *JINST*, vol. 17, p. P10005, Oct. 2022. `doi.org/10.1088/1748-0221/17/10/P10005`

[16] B. Yee-Rendon *et al.*, "Robust and compact design of a 30-MW beam transport line for an accelerator-driven subcritical system", presented at the 19th Annual Meeting of the Particle Accerator Society of Japan (PASJ'22), Kitakyushu (Online), Japan, Aug. 2022, paper FROA07, this conference.