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Fusion component failure rate database, status and evolution

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Abstract

Nuclear fusion is expected to be available as a source of energy from the middle of the present century. One key aspect of the success of this technology will be the reliability growth implemented in the design from the early phases. Nuclear fusion plants are expected to exploit many fusion plant-specific components with a relatively low technology readiness level, or in some cases exploit components with mature technology from fission plants, but within different and poorly explored operating domain windows (e.g. in terms of loads, operation regimes, etc). An important source of uncertainty in reliability assessment then resides in the failure and repair model definition for fusion plant components. To limit such uncertainty, a fusion component failure rate database was developed to collect failure and repair screening data suitable for fusion system reliability analyses. The records of the database were validated by field expert collaborative efforts and mainly consist of two categories: (i) nuclear fission data recommended values to be used for fusion applications, and (ii) data estimated from nuclear fusion research facility operating experience. First, a review of available data and the database organization status is presented. The database evolution is then described in terms of added failure and repair data records derived from engineering selection, specific component selection datasheets and failure modelling.

Keywords: failure rate, repair rate, nuclear fusion, component, database, reliability, availability

Nomenclature

AF	Availability factor
FCFRDB	Fusion component failure rate database
FMEA	Failure mode and effects analysis
FOR	Forced outage rate
FPP	Fusion power plant
FR	Failure rate
IEA	International Energy Agency
HHF	High heat flux
LCOE	Levelized cost of electricity
MTTF	Mean time to failure
OA	Operational availability
PSA	Probabilistic safety assessment
RAMI	Reliability availability maintainability and inspectability
sCD	Single-crystal diamond
UCLF	Unplanned capability loss factor
TRL	Technology readiness level

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1. Introduction

Nuclear fusion is expected to be available as a viable energy source technology in the next decades. The actual claimed date of fusion plant commercialization currently ranges from the 2030s to the 2050s depending on roadmaps proposed from the private [1] or public sectors (e.g. EUROfusion [2]). A common goal is to overcome scientific and technological challenges to obtain burning plasma and tritium self-sufficiency. In addition to the actual deployment date for fusion pilot plants, a key aspect of the success of such technology in the energy market will be the reliability of the systems and the achieved overall availability performance of the plants. When considering the current most common technologies acting as producers in the energy market, the availability factor (AF) is typically exploited as a comparative metric. The AF is defined as the ratio between the amount of time a plant is able to produce electricity over a certain period and the amount of time in the period. Table 1 reports commonly observed values for the AF [3], also assumed in energy market penetration modelling [4].

When considering historical operational experience for nuclear fission plants, the observed energy AF averaged value over all plants and the entire lifetime is about 78%. The average unplanned capability loss factor (UCLF) is 5.9% [3]. The UCLF is the ratio of the unplanned energy losses during a given period of time to the reference energy generation, expressed as a percentage. The key difference point with respect to the AF resides in the fact that plant operation and electricity production can sometimes be stopped on the basis of economic considerations. Another indicator can be defined in addition to the AF and UCLF, which is the forced outage rate (FOR). This describes the system unavailability during the scheduled operation, excluding the preventive maintenance stops. According to the U.S. Nuclear Regulatory Commission, the commercial nuclear fission fleet has an FOR of below 3% [5], a target hardly achievable future experimental fusion power plants (FPPs).

It is also interesting to note that availability and related metrics, such as the capacity factor[1], have a measured impact on the levelized cost of electricity (LCOE), which is reduced by half when the AF rises from 30% to 60% for most technologies [6].

No operational statistics are obviously available for nuclear fusion plants, but some availability targets have been established. As an example, the EUROFusion DEMO EU plant has an operational availability (OA) target of 30% and a mean inherent availability target of 48% [7]. FPP availability in market penetration analyses is assumed to be around 80%, further rising to 85% after the learning factor. Moreover, nuclear fusion as well as nuclear fission is also characterized by high capital expenditures, which means that it is economically advisable to achieve a high availability of the plant. In addition to that, and with respect to fission plants, fusion plants (assuming a tokamak concept) are further characterized by pulsed operation and a high scheduled maintenance time for in-vessel component replacement, which further reduces the OA. As a result, the modelled LCOE for fusion [8] scales as $\approx (rF/A)^{0.6}$, where r is the discount rate, F is the learning factor, A is the plant availability.

[1] Capacity factor is the ratio of the average output of a facility to its maximum output.

Table 1. Availability factor for energy production technologies [3, 4].

Tech.	Coal NatGas Bio	Nuclear fission	Hydro	Wind	Solar
AF %	75–95	80	50	20–40	10–20

In addition to reliability availability maintainability and inspectability (RAMI) considerations, reliability requirements might also be applied for safety or investment protection reasons, typically to be demonstrated at the component qualification stage.

All of the presented facts highlight the necessity to consider plant reliability/availability performance from the design early phases in order to optimize the design and minimize any unscheduled downtime. This is a challenging task since nuclear fusion plants will exploit many fusion specific components with a relatively low technology readiness level [9], or in some cases exploit components with mature technology from fission plants. Note that data derived from fission operational experience typically have higher statistical significance with respect to fusion facilities. On the other hand, fusion-specific data better represent the poorly explored domain window in harsh environments (e.g. in terms of loads, operation regimes, etc), which is known to have effects on failure rates (FRs) [10, 11]. It is in fact well known that fusion technology applications are impacted by higher energy neutron spectra and relevant fluences, capable of inducing damage in the materials up to 50 dpa [12]. Several projects are ongoing to perform material characterization under fusion-specific neutron loads, such as IFMIF-DONES [13], but qualification data at the component level are still rather scarce.

Reliability growth for the FPP design needs to be supported by means of suitable RAMI analyses [14, 15]. An important source of uncertainty in such RAMI assessments resides in the failure and repair model definition for fusion components lacking operational experience. To limit such uncertainty, a fusion component failure rate database (FCFRDB) [16, 17] was developed to collect failure and repair screening data suitable for fusion system RAMI and PSA analyses. Several types of studies are enabled by specific assessments of failure and repair data on fusion systems, such as design RAMI assessments for preliminary design phases such as for ITER test blanket module systems [18], sensitivity analysis to support a reliability-driven design at the conceptual phase [7], studies attempting to estimate the frequency of DEMO disruptions due to component failures [19], or the probabilistic safety assessment (PSA) approach to identify postulated initiating events [20] by means of failure mode and effect analyses or to identify safety classification in DEMO [21].

It should be emphasized that in the RAMI/PSA analysis it is often impossible to identify a single representative failure datum to be used for a specific fusion component. It is therefore common practice to rely on multiple sources of failure data retrieved in the literature for similar components. In such cases, either a sensitivity analysis on the min–max values for available failure data is carried out, or a single value is estimated by sampling failure distributions from multiple data sources, as done in [22].

The present work reports on the status of the FCFRDB, presented in section 2, and recent developments in terms of added records and database interface evolution in section 3.

2. FCFRDB overview

In the framework of an International Energy Agency (IEA) agreement on the environmental, safety and economic aspects of fusion power [23], an international collaborative task was defined to collect FRs for components to be used in nuclear fusion facilities.

The FCFRDB has collected data from various sources (figure 1) that are mainly categorizable into two classes:

- Records selected by experts from literature screening and judged suitable for usage in the fusion domain—about 62% of the records
- Records estimated from operational failure data in fusion experimental facilities—about 38% of the records.

Components are identified in the database according to a hierarchical taxonomy adapted to fusion facilities from the International Atomic Energy Agency component classification [24]. Components are further categorized by family name, type and four different levels of subclasses.

Six different families are currently defined (figure 2).

— Mechanic 47.3% of records
— Electric 23.5% of records
— Instrumentation and control (I&C)12.8% of records
— Fusion-specific device 15.9% of records
— Chemical 0.3% of records
— Building 0.2% of records

Each record (figure 3) consists of several fields, i.e. information related to failure mode, component boundaries, application field, operation mode and design features, failure and repair rate values including uncertainty values, type of data used to obtain statistical descriptive parameter values, data source and possible functional assignment of the component in a generic FPP. A web-accessible version of the database is available at following address: http://fus-se.frascati.enea.it:8080/Enea, made available to a community of users involved in fusion system RAMI analysis and research on failure operational statistics.

3. FCFRDB evolution

3.1. Recently added failure data

About 500 new records have been added to the FCFRDB, as summarized in table 2. Data have been either selected from literature sources as suitable for the fusion plant domain or derived from operational statistics of components. Among these data we mention data extracted from chemical process or nuclear facility plants [25] or selected as suitable for application in assessments for fusion plant ventilation systems [26] or plant electrical systems [27]. FRs selected for facilities operating with specific coolants, e.g. molten salts or liquid metals, have been taken from [28]. Data exploited in previous assessments for remote handling [29] were also extracted and processed to populate the database. Considering magnet systems exploited in fusion, failure data resulting from operational experience in DIII-D [30] were post-processed to derive failure statistics at the component level.

In addition, data derived from modelling considerations on a fast discharge unit of toroidal field coils were extracted from [31] and from acceleration applications [32, 33].

Whenever available, mean time to repair data for components have also been recorded. These data of course consider only the time necessary to repair the component from a specific failure mode and not the full recovery time, which will clearly depend on the actual plant, the environmental conditions and the logistical issues where the maintenance operation is performed.

Two examples of fusion-specific components with load-dependent FRs were also included in the database. In these examples, the FCFRDB was populated both with an experimental source datum expressed as a function of the amount of load withstood until failure and an estimate of the time to failure obtained by modelling the relationship between the load and expected usage scenario.

The first example is a mean time to failure (MTTF) estimation derived for divertor systems, exploiting qualification test data [34]. The original data reported failure events for a population of 26 divertor inner vertical target mock-ups undergoing high heat flux (HHF) tests provided in cycles (10 s flux on, 10 s off) of flux loads ranging from 10 MW m^{-2} (5000 cycles) to 20 MW m^{-2} (an additional 300 cycles). In [35], these data were analyzed exploiting a Bayesian framework coupled with step-stress accelerated life testing to provide MTTF estimates. Since i the actual HHF load that these components will undergo once installed and operated in a plant is not known, the parameter estimates have been reported for the exponential and Weibull cases (table 3). In particular, note that for the exponential distribution, the following relation was exploited in the calculation: $1/\lambda = Ce^{B/V}$, with V being the load level (e.g. 10 for a 10 MW m^{-2} thermal load), and C and B the parameters of the Arrhenius function modelling the effect of the applied load.

For the Weibull distribution, the following relation was exploited in the calculation: $\eta = Ce^{B/V}$. Note that unlike the exponential, when exploiting the Weibull distribution, a

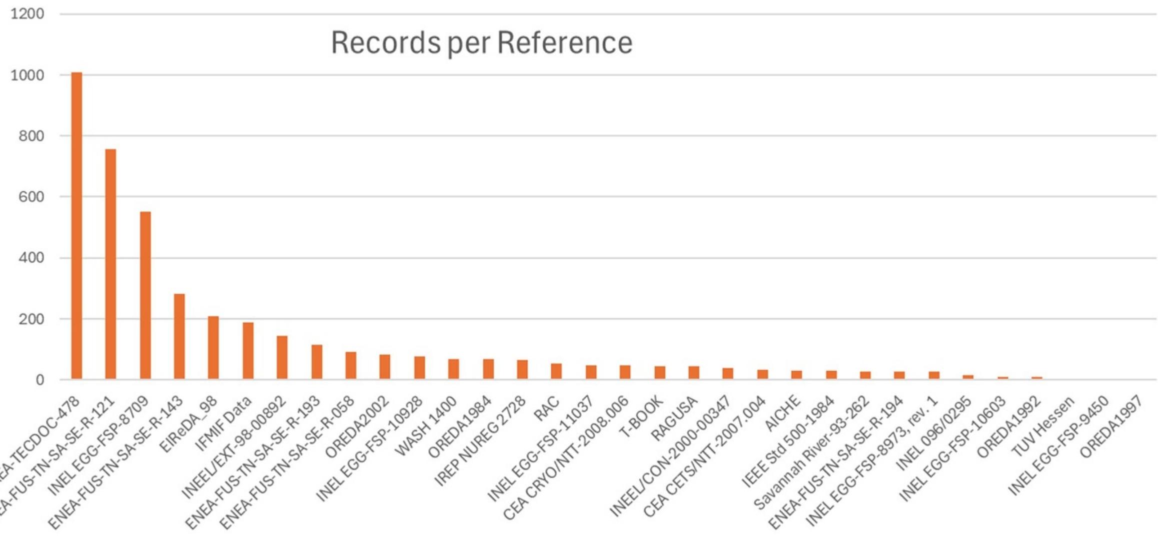


Figure 1. References for failure rate records in FCFRDB.

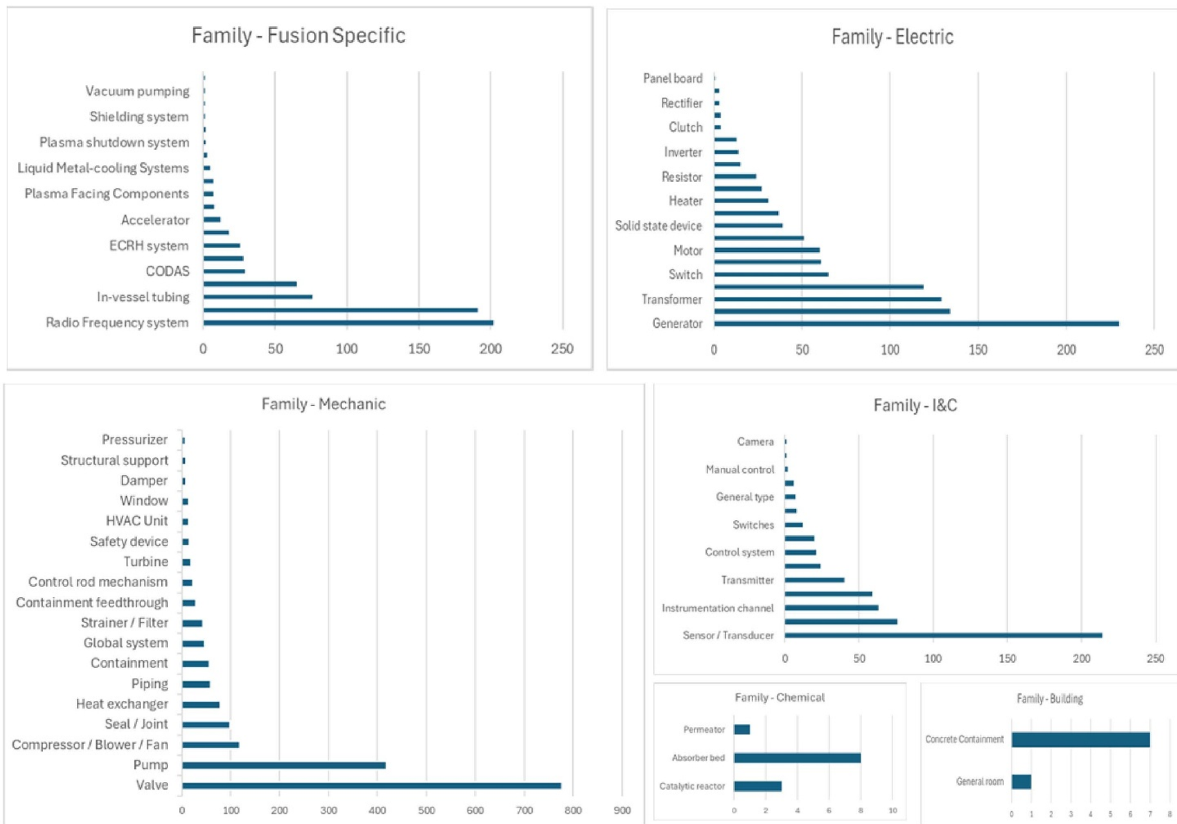
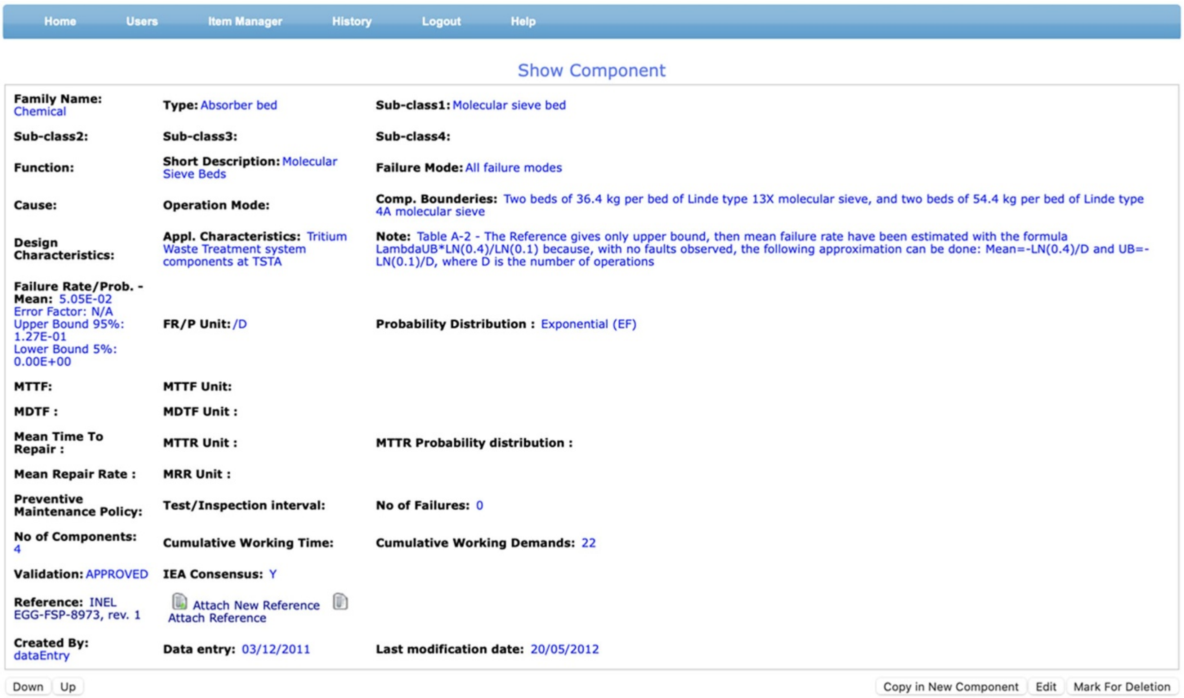


Figure 2. Number of failure rate record fields in FCFRDB by specific families.

time-dependent FR function can be extracted, depending on two parameters. For comparison's sake, an MTTF estimate when assuming 10 MW m^{-2} load is shown in table 3.

A second example of load-dependent failure estimation is the single-crystal chemical vapour deposited fast D–T neutron diamond detectors to be exploited in ITER. The actual experimental datum for this single-crystal diamond (sCD) detector was derived from [36] where the expected life is expressed in terms of max cumulated fluence of uncollided neutrons. A value of 1.0×10^{15}neutrons cm^{-2} before degradation was derived from radiation hardness tests. This source experimental datum is reported in the database, enabling adaptation for user-specific scenarios. An MTTF based on a reference irradiation scenario was also included. In particular, a mapping between the cumulated neutron fluence (n cm^{-2}) and the MTTF (h) was then obtained by exploiting the ITER


Home Users Item Manager History Logout Help

Show Component

Family Name: Chemical
Type: Absorber bed
Sub-class1: Molecular sieve bed
Sub-class2:
Sub-class3:
Sub-class4:
Function:
Short Description: Molecular Sieve Beds
Failure Mode: All failure modes
Cause:
Operation Mode:
Comp. Bounderies: Two beds of 36.4 kg per bed of Linde type 13X molecular sieve, and two beds of 54.4 kg per bed of Linde type 4A molecular sieve
Design Characteristics:
Appl. Characteristics: Tritium Waste Treatment system components at TSTA
Note: Table A-2 - The Reference gives only upper bound, then mean failure rate have been estimated with the formula LambdaUB*LN(0.4)/LN(0.1) because, with no faults observed, the following approximation can be done: Mean=-LN(0.4)/D and UB=-LN(0.1)/D, where D is the number of operations
Failure Rate/Prob. - Mean: 5.05E-02
Error Factor: N/A
Upper Bound 95%: 1.27E-01
Lower Bound 5%: 0.00E+00
FR/P Unit: /D
Probability Distribution : Exponential (EF)
MTTF:
MTTF Unit:
MDTF :
MDTF Unit :
Mean Time To Repair :
MTTR Unit :
MTTR Probability distribution :
Mean Repair Rate :
MRR Unit :
Preventive Maintenance Policy:
Test/Inspection interval:
No of Failures: 0
No of Components: 4
Cumulative Working Time:
Cumulative Working Demands: 22
Validation: APPROVED
IEA Consensus: Y
Reference: INEL EGG-FSP-8973, rev. 1
Attach New Reference
Attach Reference
Created By: dataEntry
Data entry: 03/12/2011
Last modification date: 20/05/2012
Down Up
Copy in New Component Edit Mark For Deletion

Figure 3. Failure rate record fields in FCFRDB.

Table 2. Summary of new data populating FCFRDB.

Reference	No. of records	Category	Type	Plant	System
INEEL_EXT-99-11 044	194	Nuclear facilities	Liquid	Metal	Cooling—liquid metal
INEEL_EXT-01	48	Nuclear facilities	Screening	Various	Plant electrical distribution systems
INEL-95/0422	129	Chemical process	Failure stats	INL chemical process plant	Chemical
INEEL/EXT-99-001318	26	Nuclear facilities	Screening	Various	Ventilation systems
ITER radial neutron camera	38	Fusion	Vendor data/models	ITER design	Neutron diagnostics
DRAGON-EAST data	15	Fusion	Failure stats	DRAGON-EAST	Cryosystem, lithium loop
Fast discharge unit—model	13	Fusion	Reliability model	ITER design	Magnets and PS
Accelerator application	8	Fusion	Screening	Various	Magnets
ITER blanket remote handling system	7	Fusion	Vendor data	ITER design	Remote handling
INEL_0299	5	Fusion	Screening	Various	Liquid metal
DIII-D	5	Fusion	Failure stats	D-IIID	Magnet

Table 3. Divertor MTTF estimate from qualification tests.

Method	C	B	λ	η	β	MTTF (cycles at 10 MW m^{-2})
Exponential (λ)	129	0.3	7.67×10^{-06}	—	—	1.3E + 05
Weibull (β, η)	2607	13.32	—	9876	8.84	9.3E + 03

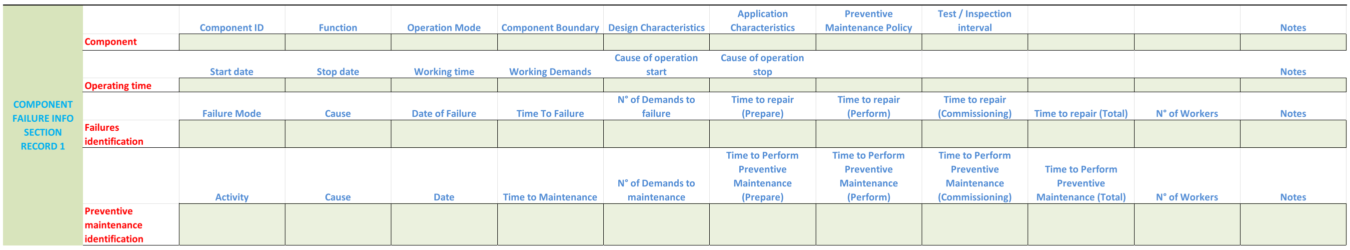


Figure 4. Sample module for new data collection.

irradiation scenario for safety assessment (SA-2), providing different fluence values for each of the 16 sCD detectors located along the various radial neutron camera (RNC) diagnostic lines of sight (LOS) [37]. With these assumptions, an MTTF averaged over all LOS from 23.76 ITER operational years was found, by assuming 4608 h per ITER operational year (excluding the calibration by alpha source hours). A fit to the lognormal distribution was performed over different times to failure across the different LOS, resulting in the following lognormal parameters: $(\mu, \sigma) = (11.60, 0.56)$ for the component lifetime.

3.2. Module developed for new raw data collection

A common situation in fusion facilities is the monitoring of global performance statistics for operation. These types of statistics are typically tailored to specific plant operation monitoring and control needs. Useful plant availability aggregated statistics can possibly be derived from such operational monitoring data. However, these data collected from a machine operation data perspective are not always exploitable from an RAMI data perspective, especially when meant for usage in other plant analyses. In fact, when assessing new systems, the connection of basic components models on the base of their contribution to system reliability is exploited to estimate the system RAMI performance. Therefore, plant-level statistics need to be disaggregated to become informative for the reliability-driven design of new systems. To enable the estimation of such data, collaborative activity is ongoing to sensitize facility operators to collect raw failure events/maintenance data at the component level. To facilitate this work, raw data collection forms were defined, as shown in figure 4. These modules were designed to be used either to extract/map the past operational experience collected in log systems onto raw data useful for the calculation of component failure statistics or to define new data collection records. Key information there is the clear definition of a low-level plant breakdown structure and the cumulated operational time for components at that defined level.

3.3. Development of new user interface

Besides the user interface available for the FCFRDB at [38], a new user interface exploiting the web interface framework in [39] is being added to enable search of records by keywords and queries, allowing for record selection based on AND/OR statements on multiple parameters as shown in figure 5.

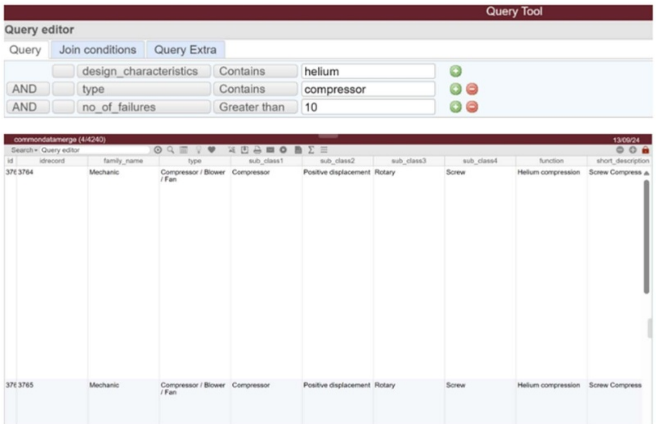


Figure 5. Example of new interface for complex queries on failure data.

4. Conclusion

A high plant availability (∼80%) is the target for nuclear fusion in order to compete in the energy market. A reliability-driven design is therefore mandatory and shall be supported by the collection of fusion facility failure and maintenance data at component level. For this purpose, an FCFRDB was developed over several years in the context of an IEA collaborative task, and is currently available to the fusion community. Failure and repair data records for components expected to be present in fusion plants were collected from three main sources: (i) data from expert selection among literature data, (ii) data from fusion-specific qualification and testing of components, and (iii) data from supplier system analyses. Data collection activity is ongoing and about ∼4700 records are now available. The development of a new user web interface enabling advanced data search is also ongoing and has been presented.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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