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A Review of Availability Growth in Energy Production Technologies[a]

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Abstract - Fusion experiments are operated to gain knowledge that will allow fusion energy to become an electricity producing technology. The current generation of fusion experiments, such as the DIII-D and Alcator C-MOD experiments, and the formerly operated Tokamak Fusion Test Reactor, do not operate as much each year as typical electricity generating power plants. The main reasons for the reduced operational availability are budget limitations to purchase electrical power to operate the experiments, downtime for device reconfiguration or alterations to perform new experiments, and downtime for repairs to the experiments. There has been speculation in some fusion power plant design studies about the plant operational availability that can be reached by mature plants. This paper shows the trends in growth of operational availability experienced in mature energy production technologies and selected types of experimental power plants to illustrate the growth pattern that fusion power plants will likely follow.

INTRODUCTION

Fusion electric power plants are expected to follow an availability growth curve as they mature. This paper reviews analogous growth patterns for the nuclear fission power reactor industry and other electrical energy production technologies. Fusion power development will probably follow a similar growth pattern. The typical pattern is that as a new technology is introduced on a practical size scale, the initial prototypical units do not have high operational availability. Even after the pre-operational testing phase to bring a new power plant into operation is completed, there is still a cautious approach to operation. The plant may not be run at full capacity; that is, the plant may be derated until the staff is comfortable with running at higher outputs. Conservative safety limits are imposed in operation, new equipment has break-in periods and infant mortality-type failures, and the staff must learn the maintenance and inspection procedures for specialty equipment. These and other factors lead to low operational availability values in the first few years of operation. For example, the prototypical pressurized water reactor, the Shippingport nuclear power plant, was expected to have an operational availability of almost 70% in the first year after it was commissioned. The plant did not meet that goal. An operational availability of 70% in the first year of operation is rather high, but not unreasonable, for a newly introduced technology.

The area of reliability growth management recognizes that prototype units using complex technical advances will invariably have significant reliability and performance deficiencies that cannot be foreseen in early design stages. The prototypes must be tested to identify problems so that improvements in system design can be made.[1] The data in this paper show that there is a recognized “stair step” of reliability growth in new technologies that is evidenced by availability growth in power plants. Fusion power plant availability is expected to grow in a fashion similar to that of fission and other power plants because of similarities between existing fusion experiment and fission test reactor availability. Present fusion experiments have achieved operating efficiencies between 60 to 80% for scheduled experiments. This range of values is similar to fission test reactors. These reactor experiences are briefly reviewed.

FISSION TEST REACTORS

The first US fission test reactors, such as the Materials Testing Reactor (MTR, 1952-1970), the Engineering Test Reactor (ETR, 1957-1981), and the Advanced Test Reactor (ATR, 1967-present) at the Idaho National Engineering and Environmental Laboratory (INEEL), did not operate 100% of the time. The purpose of these reactors has been to generate neutrons for materials irradiation. Material samples were loaded into, and then removed from, the reactor core. These reactors typically operated for a few weeks at a time and then were shut down for a few days or a week to perform material sample changeouts and sometimes fuel changeouts as well. Irradiation test reactors often compare the actual operation time to the scheduled operation time (operating efficiency) rather than comparing actual operation time to calendar time (calendar availability). Data are scarce for the MTR and ETR, since these reactors were both shut down some time ago, but historical data exist for the ATR.[2] In the early years of its operation, the ATR suffered from many spurious scrams generated by instrument noise, control rod drops, and the restrictive operating bands placed on the reactor safety instrumentation. Over the first ten years of plant life, 2:3 voting logic was introduced into the scram signal logic circuits, which ended the noise-induced scrams. The control rod electromagnet systems were redesigned, ending spurious rod drops. The instrumentation operating bands were relaxed slightly as more experience was gained with the plant. Figure 1 shows the ATR operating history through 1997. The earliest years (1967-1970) are not plotted. Those years were very low availability (under 33%); the plant dealt with problems of heat exchanger tube vibration, adding extra air cooling for the main pump motors, water hammer with large check valves, and other engineering problems. The equivalent availability curve shows that in early life, the plant had some technical problems that held it to low levels of operation (beryllium used as a neutron reflector cracked and required early replacement). Comparing the operating efficiency and equivalent availability curves shows what outages had been planned for and which outages impacted operations. The 1972 and 1993/94 events adversely impacted the operating schedule. From the graph, the last few years have shown ATR to have operating efficiencies in the 90% range and nearly 80% calendar availability, which is high for a test reactor.

Other fission test reactors have also reported their operating efficiency. The High Flux Isotope Reactor reported efficiency in the 40 to 60% range,[3] and the Fast Flux Test Facility (FFTF) with a 60 to 100% range.[4] The FFTF calendar availability began at 38% in its first year and then stair-step increased to 65% the next year. The calendar availability then incrementally increased in following years to the 75-80% range. The Experimental Breeder Reactor II, which produced electrical power for the INEEL site, had an operational calendar availability in the 70 to 80% range during its middle life and end of life.[5]

As discussed with ATR, all of these reactors showed early life problems with equipment (pumps, valves, heat exchangers, instruments)[6] that had to be resolved, and difficulties that arose as the plant operations and maintenance personnel learned about the new plant, adjusted procedures, etc. Other fission training reactors have exhibited some of the same types of difficulties during initial startup. For example, the University of Missouri Research Reactor at Columbia, Missouri had difficulties with spurious control rod drops, control rod drives, and neutron instrumentation.[7] That facility did not have many novel design features; it was not unique among other research reactors but still suffered from these equipment problems. These problems did not cause safety concerns, but they were operational inconveniences that added downtime for repairs during the early life. The reactor also stair-stepped its way to increased availability by repairing equipment and amending procedures.

PROTOTYPE FISSION POWER PLANTS

Some of the earliest power reactor demonstrations, such as the Pathfinder and Vallecitos boiling water reactor demonstrations, do not have much locatable information about their operating experiences. The Shippingport pressurized water reactor (PWR) and the Dresden I boiling water reactor (BWR) have better documentation of their operating experiences. Table 1 gives some annual operating hours for the first years that these plants operated.[8,9] Some of the most impressive step increases in operating time were exhibited by Dresden I (1961 to 1962) and Yankee Rowe (1960 to 1961). In general, the increasing operating hours per year shows the typical trend of ‘debugging’ or ‘break-in’ that is customary with new facilities. Pre-operational testing programs typically uncover minor equipment faults and sometimes design discrepancies. Startup of any large plant usually uncovers other problems, some minor and some that can be significant. Initial startup operation may be referred to as shakedowns, trials, debugging, break-in, or other terms, but the idea of correcting problems during initial field operation is noted in many technologies.

The Shippingport reactor had its share of problems that caused downtime in the first year of operation. Shippingport went critical for the first time on December 2, 1957; exactly fifteen years after the first controlled chain reaction at Stagg Field. On December 18, 1957, the Shippingport reactor went “on-line” by making electricity for the electrical utility grid. Shortly afterward, in 1958, the Shippingport PWR needed to replace a main coolant pump whose shaft had warped, reduce drift in hydraulic operated pilot valves on the primary system, control relief valve leakage past the valve seats, and repair leaks in two tubes of one of the steam generators. Some design deficiencies in instrumentation and controls were also recognized and corrected.[9] The first refueling outage for Shippingport took place between November 2, 1959 and May 7, 1960.[10] By today’s standards, where less than two months are typically needed for a refueling outage, a 6-month time interval is extremely long. Shippingport personnel used only about twenty days to replace the 32 fuel assemblies, and the remaining time was used for correcting problems encountered during operation, and install some new equipment. A recommendation for a major modification to future designs was made: change the reactor vessel head so that it would no longer be the terminus of reactor-core performance instrumentation; that instrumentation and its supports caused access and clearance problems throughout refueling. Shippingport was intended to operate for 3,000 full power hours on the first core (3000/8760 x 100 = 34.2% availability possible) and 7,500 full power hours on the second core (7500/8760 x 100 = 85.6% availability). The first core life was doubled to 6,000 hours (6000/8760 x 100 = 68.4% availability possible) because the fuel design was so conservative, and it was actually operated somewhat longer.[11] Table 1 shows that Shippingport exhibited a steady growth in on-line time over the first seven years of plant operation.

The Dresden I BWR first produced electricity in April 1960, and began commercial service in October 1960. Then in November 1960 the plant went into an outage to modify its control rods and control rod drives. The plant restarted in June 1961 and ran at 100% availability until October 2, 1961, when it was shut down for a license inspection.[12] The plant had its first refueling outage in the fall of 1962 and did not restart until March 1963; the remaining time in 1963 saw almost 500 hours of forced outage time for repairs to balance of plant equipment (turbines and switchyard). The initial plan for Dresden I was to achieve 70% availability; operating for four years on the same reactor core and then have a 6-month refueling outage.[13]

MATURE POWER PLANTS

As experience in the fission industry grew, many factors contributed to power plants increasing their availability. Establishing best practices in maintenance and operations allowed personnel to treat equipment better, plan tasks for better time utilization, and scheduled maintenance sessions made a positive impact in equipment on-line time. Pre-operational testing of systems allowed early identification of some of early failures (infant mortality) in major plant components. Personnel training and procedures also improved.[14] Equipment manufacturers began to get operating experience feedback that allowed them to tailor their equipment to the needs of the customers. In the 1970's and early 1980's, the average annual availability of US PWRs and BWRs varied in the range of 70 ± 10%, and coal fired plants were also in this range.[15]

In the 1990's, US PWR and BWR availability has improved. In 1995, PWRs averaged slightly over 83% availability, and BWRs averaged almost 78% available.[16] The overall average availability of US nuclear power plants was 81.7%. The electrical utilities have made an effort to bring new plants (those starting in 1983 and after) on line more smoothly,[17] and the electric utilities have also held a campaign to reduce scram events.[18] Many fission plants around the world have been exhibiting availability in the 80 and 90% range.[19] The combination of safety consciousness, design and operations practices, personnel training, and enhanced maintenance have all increased plant availability.

To compare these fission power plant values with coal-fired power stations, Table 2 gives some data for coal-fired fossil steam units, all megawatt sizes.[20] The plant capacity weighted service factor (hours the unit was electrically connected to the power transmission system) is given as the availability value. In the 1960's and 1970's, fossil fuel power plants performed slightly better than fission plants, and both have experienced availability growth over time. For 1995, the PWR fission plants averaged slightly better than coal fired plants, while BWR fission plants were not quite as available. The incremental growth into the 80% range has been driven by economic factors.

Other energy production technologies in the US are not operated as continuously as coal and nuclear units. Gas turbines, for example, have not exhibited the same level of availability growth as coal-fired and nuclear power plants. Their service factors are in the 2 to 5% range from 1982 to 1997.[20] Intermittent operation allows more maintenance opportunities than steady-state operation, so an operating plateau is easily reached. Geothermal plants (all megawatt sizes) have shown some incremental availability growth in the 1982 to 1997 time frame, growing from service factors in the 75% range to a peak of 90%.[20]

AVAILABILITY ESTIMATES FOR FUTURE NUCLEAR POWER PLANTS

Fission reactor designs for the future have even more aggressive availability goals. The US Advanced Light Water Reactor has utility requirements that call for 87% availability over its 60 year life, a 24-month refueling interval, and an unplanned shutdown (scram) frequency of less than 1/year.[21] Other reactor designs also call for high availability. The European Pressurized Water Reactor also calls for an 87% availability over a 60 year lifetime.[22] A Korean design study noted that Korean fission plants already have had average availability values in the 85 to 88% range for the past several years. Therefore, they set a 90% availability goal for a next generation reactor.[23]

CONCLUSIONS

There is a definite trend in the growth of availability for new power plants. The majority of power plants begin their operational lives with a low availability value, perhaps in the 30% range, and then the yearly on-line time grows. Some early fission reactors had 'stair-step' growth of doubling their on-line time in a year. Most of the early fission plants had growth into the 70% range as an average value. The current generation of mature fission plants now have availability averages around 82%. Future fission reactor designs have plans for 87% and higher availability. Initial fusion power plants are expected to start with low availability and increase over time just as fission plants have done. An engineering goal for fusion power plants should be an availability range that is comparable to those from fission power plants. This goal would be one of many steps to assure that fusion power is competitive with fission power.

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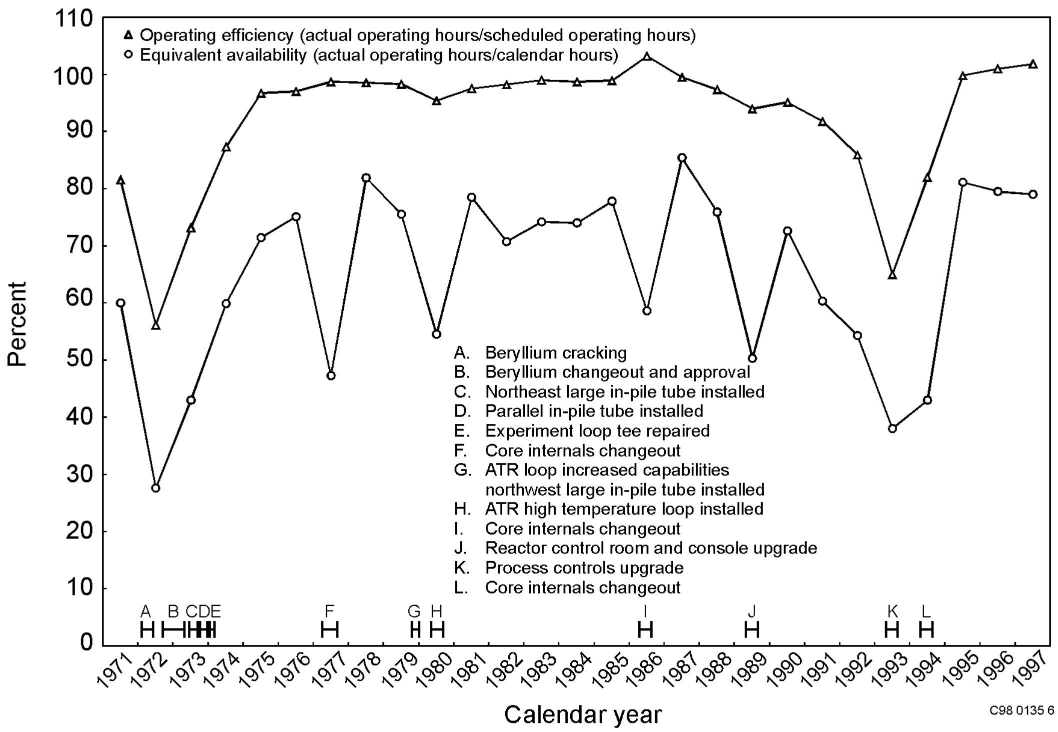

FIGURE 1. ATR OPERATING EFFICIENCY AND EQUIVALENT AVAILABILITY FACTORS

TABLE 1. EARLY FISSION POWER PLANT OPERATING AND STANDBY HOURS

Plant Name	**Calendar Year**							
	1957	**1958**	**1959**	**1960**	**1961**	**1962**	**1963**	**1964**
Shippingport PWR	250	5,000	5,400	5,900	7,000	7,700	7,800	900
Dresden I BWR	na	na	na	3,873	3,520	7,061	7,071	7,265
Yankee Rowe PWR	na	na	na	1,151	6,913	4,725	6,856	7,973
Big Rock Point BWR	na	na	na	na	na	na	4,201	3,758

na indicates that the year is not applicable; that is, pre-startup for that power plant

TABLE 2. FOSSIL-STEAM UNIT AVERAGE AVAILABILITY PER YEAR

	Calendar Year							
	1982	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**
Availability, %	72.48	73.06	74.0	74.37	73.47	74.82	76.39	76.52
	1990	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**
Availability, %	77.52	76.87	76.82	78.79	78.68	79.47	82.07	83.65
Note: This table presents capacity weighted service factors, the most comparable value to the NRC reported availabilities given above. Service factors only account for the time a plant was connected to the electrical power grid, not the reserve time that a power plant could have been operating but was not for economic or power grid reasons.								