How Military Development of Nuclear Submarine Technology Influences Nuclear Power Plant Development and Adoption.

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Introduction

Military pursuits motivate nations to pursue innovative technologies that provide advantages over adversaries. These technologies often have utility beyond the battlefield with an impressive list of innovations including the internet developed under the United States (US) Department of Defense (DoD) Advanced Research Projects Agency (ARPA) in 1969, the Global Positioning System (GPS) developed with NAVSTAR satellites in 1983, and personal voice assistants like Siri which all began under DARPA's Personalized Assistant that Learns (PAL) program [1].

This report will show that this pattern of military innovation driving wider commercial and public use extends to nuclear reactor technology. Specifically, this report will show that nuclear reactor technology development for nuclear-powered submarines developed by the world's military superpowers—United States of America, United Kingdom, Russia, and People's Republic of China—has a consistent and significant impact on the development of commercial and public nuclear power plants.

Background

It's important to understand the differences between military and commercial nuclear reactor technology to appreciate the realistic limits of transitioning military nuclear reactor technology to commercial plants. Nuclear reactors in submarines must react quickly to dynamic environments with the ability to change reactor power output levels from idle to maximum power on the scale of seconds. In contrast, nuclear power plants ramp up to maximum power levels on the scale of hours. Moreover, submarine reactors have size constraints and extended refueling requirements that require submarines cores to use high enrichment fuel enriched to more than 80%, while commercial reactors use low enrichment fuel enriched 3-5% [2]. This difference in enrichment corresponds to a reactor cylinder size of approximately 3 feet across and 3 feet tall for high-enrichment submarines and a cylinder size of 13 feet across and 13 feet tall for low-enrichment uranium.

A key design element of nuclear reactors is the coolant medium. The two common designs are Pressurized Water Reactors (PWR) and Liquid Metal Cooled Reactors (LMR). By immersing the fuel rods in liquid metal with high thermal conductivity, heat is more effectively removed from the reactor vessel, enabling a higher power density and power output than PWR counterparts. The disadvantage of LMRs include difficulty of inspection and repair and fire hazard of alkali metals (this may be why LMR Russian submarines have had disastrous accidents than PWR US submarines). PWR reactors require pressurized water to prevent boiling in the reactor vessel which presents its own challenges. However, PWRs are more stable with temperature changes than LMRs and are easier to operate and maintain. For those reasons, all but one US nuclear submarine has been powered by PWR along with most commercial nuclear power plants [3].

Nuclear Reactor Data

To investigate the relationship between military nuclear reactor technology development and adoption to commercial and public transition, data has been collected from many public sources. Nuclear power plant data was sourced from the International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) [4]. Nuclear reactor information for submarines was sourced from US Navy Fact Files [5], Naval War College Review [6], and the National Museum of American History Archives [7]. All the data aggregated for this report is compiled and shared in the Appendix across five tables—one for each country (US, UK, China, Russia) and one aggregate table.

A first look at the aggregated data in Figure 1 shows the number of operational nuclear power plants and operational nuclear submarines from 1950 through 2020. It's clear that the United States and Russia are world leaders in nuclear submarine technology, while the US and UK have the first lead on nuclear power plant development. In both cases, China lags, but is showing rapid growth in nuclear power plant development. The proceeding analysis will explore the relationship between these charts as well as their relationship to policy and nuclear disasters.

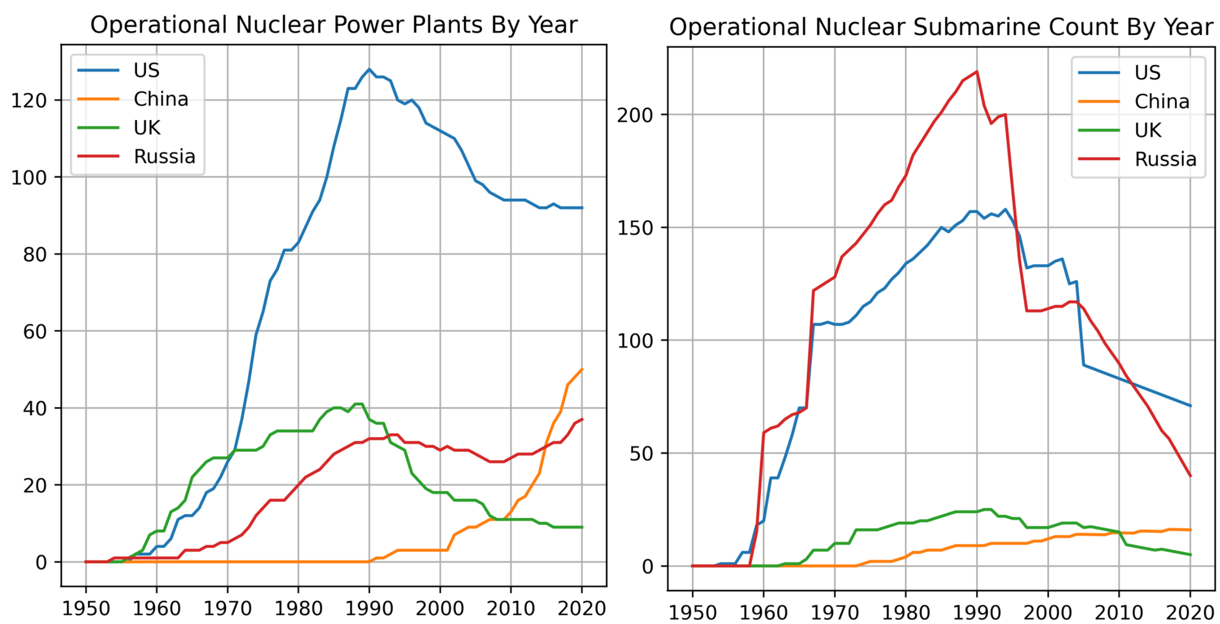

Figure 1: Number of operational nuclear (left) power plants and (right) submarines per country by year from 1950 to 2020.

Submarine vs Power Plant Nuclear Reactor Development

Figure 2 plots each country's nuclear submarine and power plant count by year from 1950 to 2020 with indicators for key nuclear disasters and policy. Key nuclear disasters include sunk nuclear submarines and power plant meltdowns. Key policy includes the START I Treaty which ended the Cold War and various nation-specific energy policies. Years where the number of nuclear submarines leads the number of nuclear power plants is shaded lightly, while darker shading indicates years when nuclear power plant count leads nuclear submarine count.

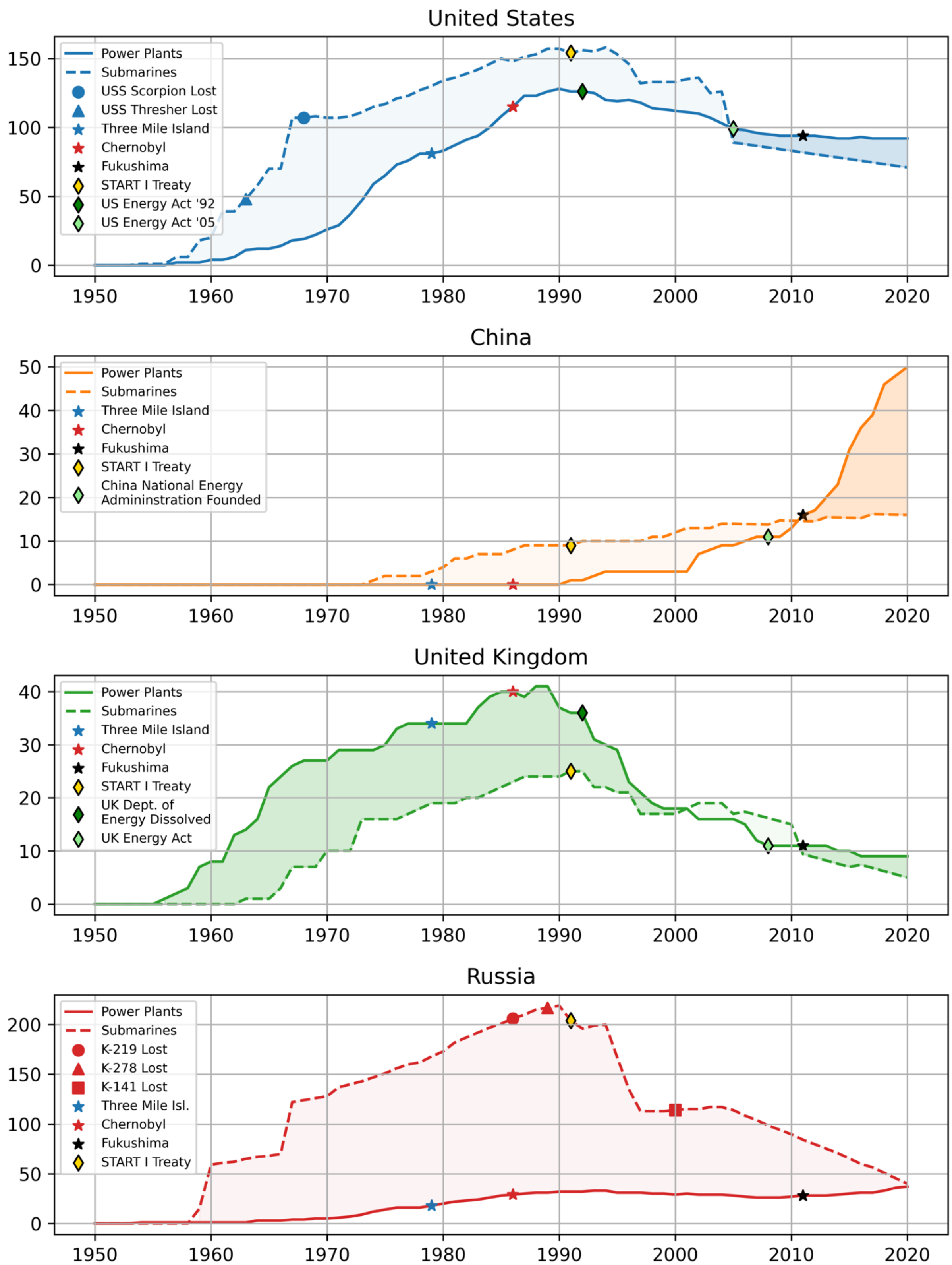

Figure 2: Number of operational nuclear submarines vs operational nuclear power plants by year (1950-2020) per country with indicators for major nuclear disasters and energy policy.

One evident trend in Figure 2 is the leading development of nuclear submarines prior to development of nuclear power plants for all countries except the UK. UK's leading nuclear power plant development might be attributed to the strong US-UK alliance allowing the UK to rely on the US nuclear submarine fleet. For the United States, the increase in nuclear submarine development continued through the loss of USS Scorpion and USS Thresher, neither of which were concluded to have been lost due to failure of the nuclear reactors. Instead, the failures were insufficient welding or accidental torpedo activation which helps explain why nuclear submarine development continued and there was no transition to diesel submarines. For Russia, however, the major losses of K-219 and K-278 may have had an impact on future development of Russian nuclear submarines. K-219 and K-278 were lost to an internal missile explosion and electrical fire respectively, not nuclear reactor issues, but the coinciding START I Treaty makes it difficult to evaluate the effect of those submarine disasters on Russian nuclear submarine development.

The Strategic Arms Reduction Treaty (START I) signed in 1991 was a bilateral agreement between the United States and then Soviet Union to reduce and limit strategic offensive arms including nuclear warheads and intercontinental ballistic missiles (ICBMs), both of which were carried as a primary role by nuclear submarines for both sides. In the following two decades, nuclear submarine fleets decreased by 56% in the US, 52% in the UK, and 45% in Russia. It appears that the arms treaty was orders of magnitude more influential in changing the rate of nuclear submarine development than submarine disasters. China is an outlier here, being unaffected by the treaty or disasters given the infancy of its nuclear submarine program. China continued to steadily grow its nuclear submarine fleet.

The same disaster and policy comparison can be made for nuclear power plants across countries. Three major nuclear disasters impacting the world's perspective on nuclear energy were Three Mile Island in the US (1979), Chernobyl in Russia (1986), and Fukushima in Japan (2011). Each of these is shown along the trend line of nuclear power plant development in each country in Figure 2. In the US and UK, the development of nuclear reactors in each country decidedly stagnates in the late 80s before the signing of START I, before the US Energy Act of 1992, and before the dissolution of the UK Department of Energy. By the time each of these events occur, the UK, US, and Russia all see stagnation or decline, meaning there was possibly a public shift away from trust in nuclear power the preceded the energy policies of the early 90s. Once the UK Department of Energy dissolved and the US passed the Energy Act of 1992, both countries saw significant declines in the nuclear reactor development, apparently allowing reactors at the end of their lifespan to be decommissioned without building replacements.

A helpful insight into the effect of policy versus disaster is Russia's lack of environmental and nuclear policy. Despite nuclear plant disasters and in the absence of drastic energy policy, Russia's nuclear energy production remained steady during the same period the UK's declined by 75%. This could indicate that policy is more influential than nuclear disasters and public trust in nuclear, and perhaps lack of public trust in nuclear energy is not as significant of a force. Finally, the differences in government structures are ignored here as it's out of scope for this report, but it certainly has some impact on nuclear development trends.

Submarine Energy for Household Consumption

This section provides an understanding of the scope of nuclear submarine power relative to nuclear power plant capacity and nationwide household energy consumption. The top row of Figure 3 shows the households per country by year and the cumulative nuclear submarine peak power per country by year for the US, UK, and Russia. The bottom row of Figure 3 uses the average instantaneous usage per US household (1600 kW in 2023) [8] as an approximation for calculating the total nuclear submarine and power plant power as a percent of instantaneous household power consumption for each country. This shows the US nuclear power plant peak capacity is 78% (96 GW) of the instantaneous demand of 123 GW, which aligns with known nuclear net electricity generation capacity of 95.55 GW [9]. Therefore, we know this analysis is accurate for extension to nuclear submarine analysis. Interestingly, the percentages of peak power generated by nuclear submarines relative to household consumption peaks at 27% for Russia in 1990, 13.5% for the US in 1992, and 7% for the UK in 1991. This is of course only for peak power capacity and not sustained operational capacity, but it shows that the nuclear submarine fleets are generating a serious amount of nuclear energy, giving credibility to the notion that nuclear submarine technology was influential in advancing public nuclear energy.

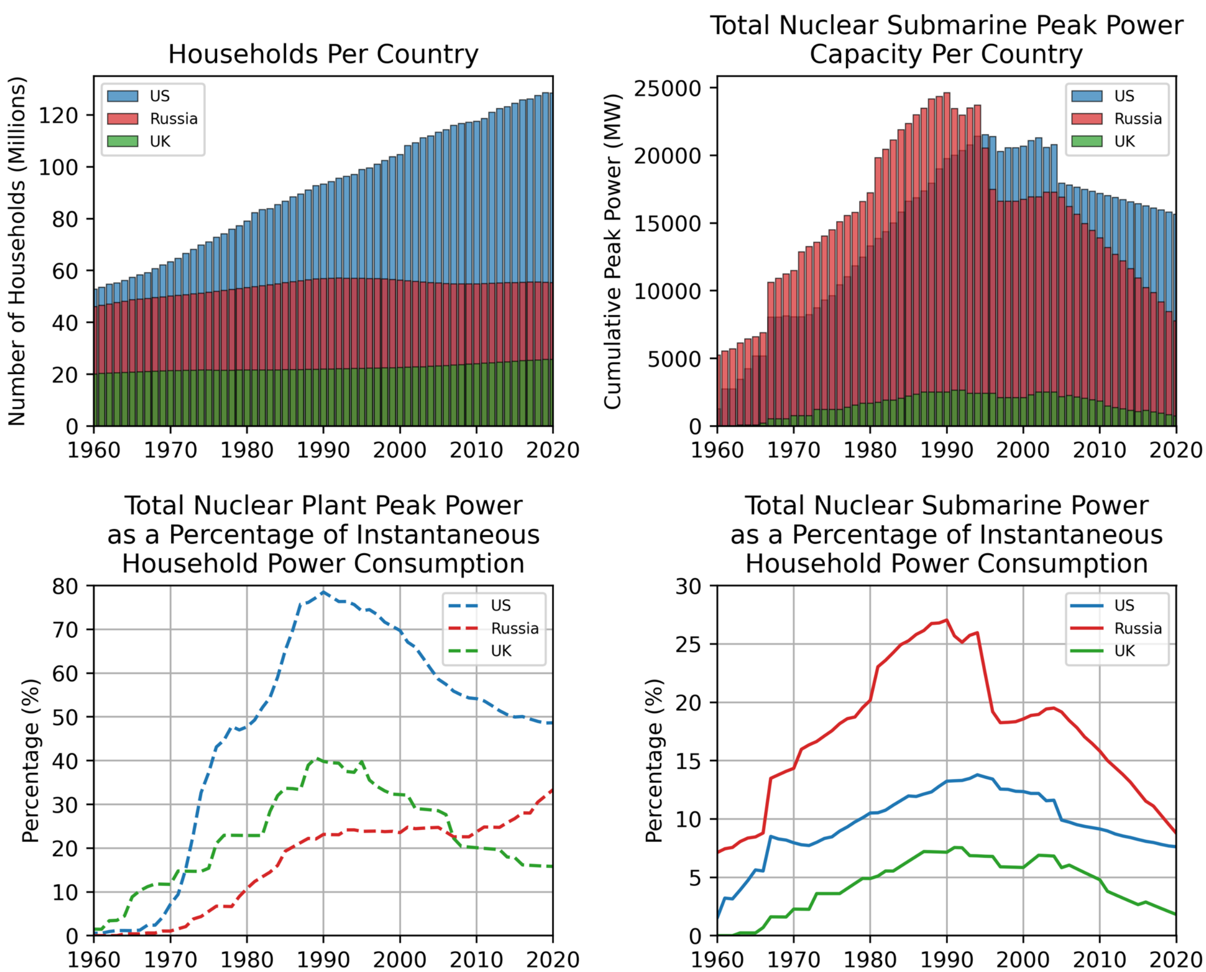

Figure 3: Nuclear submarine peak power capacity as percentage of household consumption.

Learning By Doing: Transitioning from Submarines to Power Plants

This section demonstrates that all global superpower's development of nuclear power plants and adoption of nuclear energy was consistently preceded by military investment in development of nuclear reactors for submarines two decades prior. One way to frame this is with the economic theory of learning-by-doing, where the nuclear industry can extract lessons learned, best practices, new supply chains, and innovations from military applications into commercial applications. To show this learning-by-doing realized in nuclear reactor technology's transition from military to commercial applications, the average peak power for nuclear power plants and submarines is plotted in Figure 4. Then, a linear regression is done per decade as a measure of innovation growth.

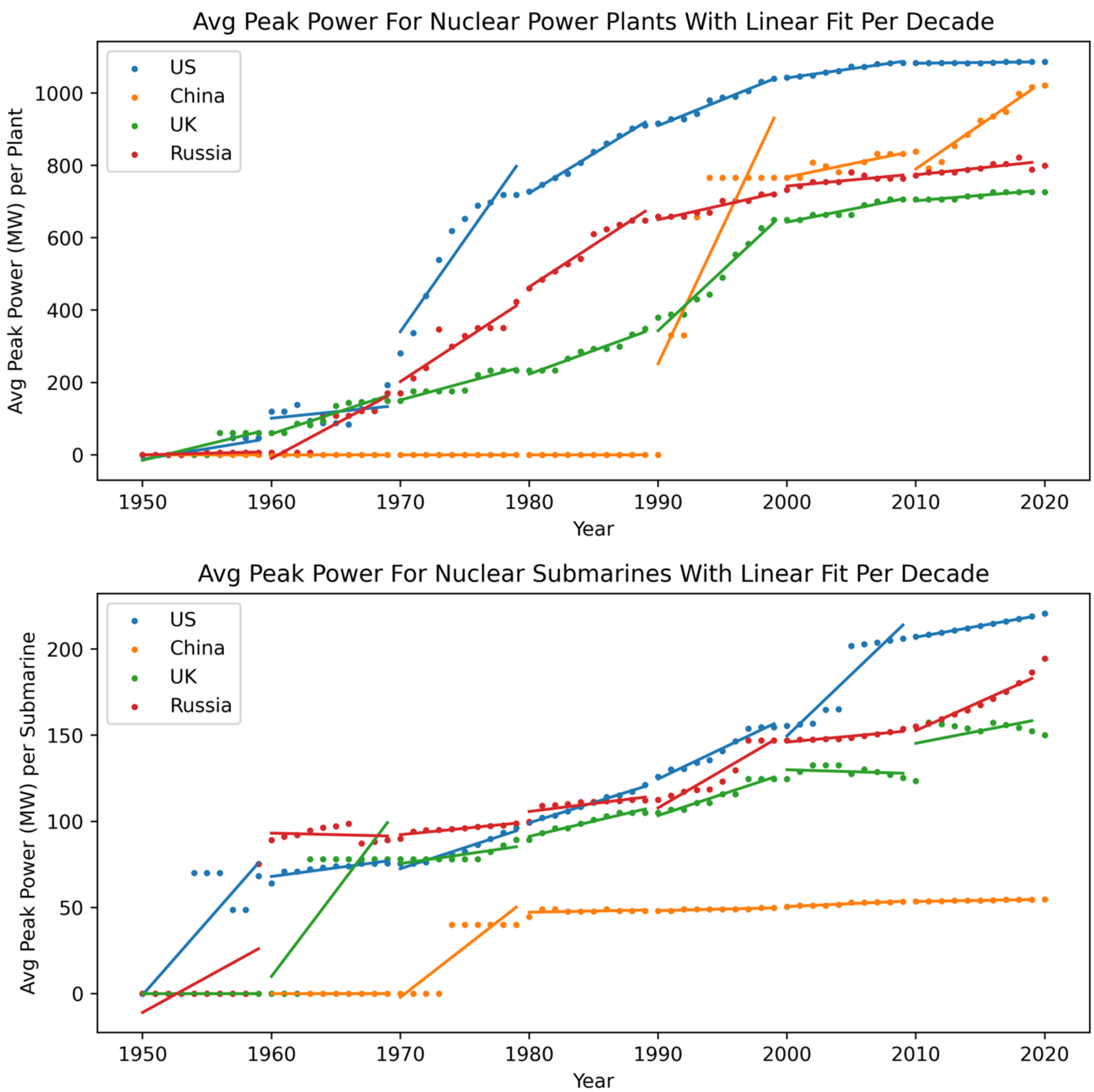

Figure 4: Average peak power for nuclear (top) power plants and (bottom) submarines.

The result in Figure 4 shows steady growth over most decades for each country and technology. However, each country has one decade with a steep rise in average peak power, indicating an innovation breakthrough via learning-by-doing. What's more, the rate of change for each decade representing the growth of nuclear technology innovation can be plotted as shown in Figure 5 to reveal a significant relationship. Figure 5 shows that the peak in annual innovation growth for nuclear power plants consistently occurs 2 decades after the peak in annual innovation growth for nuclear submarine technology. This shows a clear example of learning-by-doing for each country from the military application of nuclear submarines to the commercial and public application of nuclear power plants.

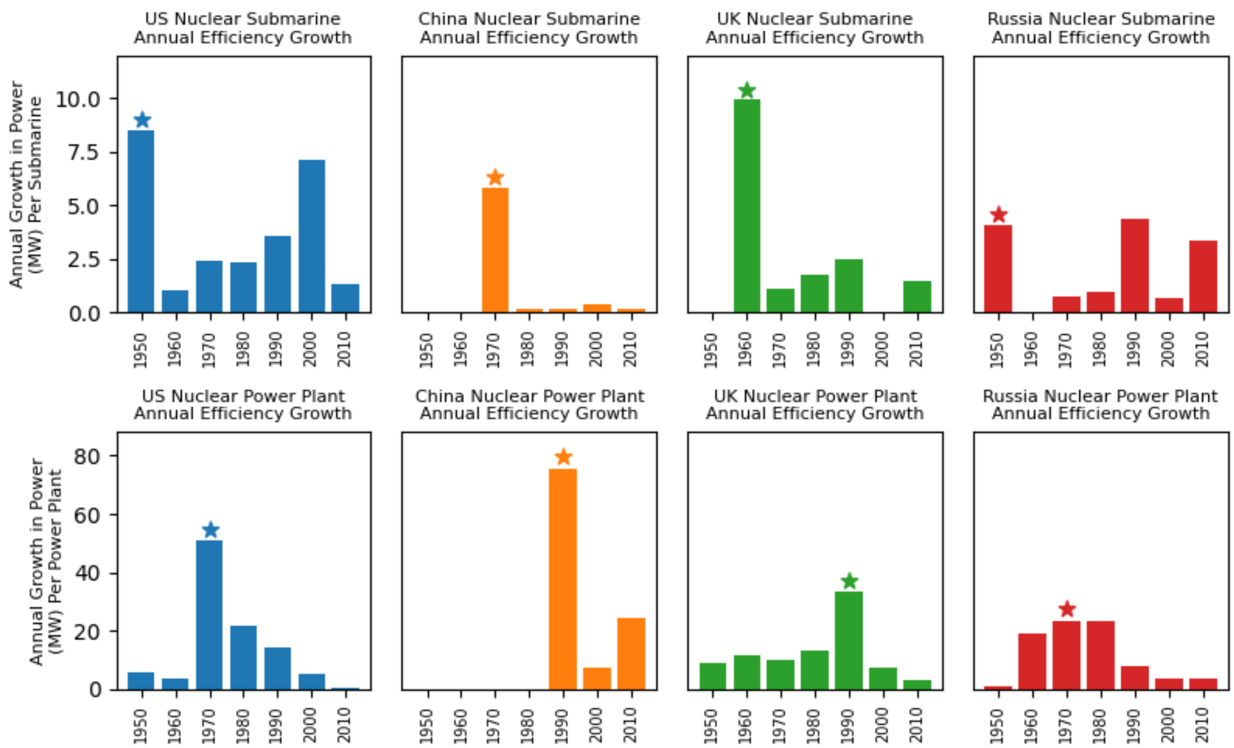

Figure 5: Annual growth in average power per (top row) nuclear submarines and (bottom row) nuclear power plants. Stars indicate peaks corresponding to learning-by-doing phenomenon from nuclear submarine technology to nuclear power plant technology two decades later.

Conclusion

It's clear that a country's development and adoption of nuclear power plants for energy production is influenced by its investment in the military application of nuclear reactors for submarines. However, diplomacy, energy policy, and nuclear disasters also play a role in influencing the development of nuclear technology which can be difficult to tease apart from the influence of previous military technology development. Next steps for this research include evaluating the role of classification of nuclear technology and how it might inhibit commercial technology development and perhaps help explain the consistent delay between nuclear reactor development for submarines and commercial power plants.

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Appendix

United States Nuclear Submarine Data

Name/Class	Built Start	Built End	Commis-sioned	Decommi-ssioned	Reactor	Number Reactors	PWR (MW)	Turbine (MW)	Speed Knots	Crew	Count	Active	Retired
USS Nautilus	1952		1954	1980	S2W	1	70	10	23	105	1	0	1
USS Seawolf	1953		1957	1987	S2W	1	70	11	23	101	1	0	1
Skate Class	1955	1959	1957	1989	S3W	1	38	6	22	84	4	0	4
USS Triton	1958		1959	1969	S4G	2	78	34	27	172	1	0	1
USS Halibut	1959		1960	1976	S3W	1	38	6	20	97	1	0	1
Skipjack Class	1956	1961	1959	1990	S5W	1	78	11	33	93	6	0	6
USS Tullibee	1960		1960	1988	S2C	1	13	2	15	66	1	0	1
George Washington Class	1958	1961	1959	1985	S5W	1	78	11	22	112	5	0	5
Ethan Allen Class	1959	1963	1961	1992	S5W	1	78	11	22	140	5	0	5
Permit Class	1958	1967	1961	1996	S5W	1	78	11	28	112	14	0	14
Sturgeon Class	1963	1975	1967	2004	S5W	1	78	11	26	107	37	0	37
Lafayette Class	1961	1964	1963	1994	S5W	1	78	11	21	140	9	0	9
James Madison Class	1962	1964	1964	1995	S5W	1	78	11	21	140	10	0	10
Benjamin Franklin Class	1963	1967	1965	2002	S5W	1	78	11	21	140	12	0	12
USS Narwhal	1967		1969	1999	S5G	1	90			107	1	0	1
USS Glenard P. Lipscomb	1973		1974	1990	S5W	1	78	11	23	131	1	0	1
Los Angeles Class	1972	1996	1976		S6G	1	165	24	20	129	62	26	34
Ohio class	1976	1997	1981		S8G	1	312	26	20	155	18	18	0
Seawolf Class	1989	2005	1997		S6W	1	270	39	35	140	3	3	0
Virginia Class	2000		2004		S9G	1	210	30	25	135	22	22	0

United Kingdom Nuclear Submarine Data

Name	Built Start	Built End	Commissioned	Decommissioned	Reactor	Active	Retired	Number	PWR (MW)
HMS Dreadnought	1959	1960	1963	1980	S5W	0	1	1	78
Valiant Class	1960	1963	1966	1994	RR	0	2	2	78
Resolution Class	1964	1968	1967	1996	RR	0	4	4	78
Churchill Class	1964	1967	1970	1992	RR	0	3	3	78
Swiftsure Class	1967	1970	1973	2010	RR	0	6	6	78
Trafalgar Class	1977	1986	1983			1	6	7	150
Vanguard Class	1986	1998	1993		RR	4	0	4	150
Astute Class	2001		2010		RR	5	5	5	200

China Nuclear Submarine Data

Name	Built Start	Built End	Commissioned	Decommissioned	Reactor	Active	Retired	Number	PWR (MW)
91	1974	1990	1974			3	2	5	40
92	1981		1983			1	0	1	58
93	1980	2009	2006			6	0	6	58
94	2000		2007			6	0	6	58

Russia Nuclear Submarine Data

Name	Built Start	Built End	Commissioned	Decommissioned	Reactor	Active	Retired	Number	PWR (MW)
November Class	1957	1963	1959	1990	VM-A 70	0	14	14	70
K-27	1958		1963		VT-1	0	1	1	146
Hotel Class	1956	1960	1960	1991		0	8	8	60
Echo I Class	1960	1965	1960	1994		0	5	5	66
Echo II Class	1960	1965	1960	1994		0	29	29	104
K-222	1963	1970	1970	1988		0	1	1	118
Yankee Class	1964	1974	1967	1995		0	34	34	100
Delta Class	1972	1990	1972			6	28	34	82
Charlie Class	1964	1979	1967	1996		0	17	17	11
Victor Class	1959	1988	1967		VM-4P	2	46	48	150
K-278	1978	1983	1983	1990	OK-650	0	1	1	190
Alfa Class	1968	1981	1971	1996	OK-550	0	7	7	155
Yasen Class	1993		2013		OK-650KPM	4	0	4	200
Borei Class	1996		2013		OK-650V	7	0	7	200
Typhoon Class	1976	1989	1981		OK-650	0	6	6	380
Sierra Class	1979	1992	1984		OK-650	4	0	4	190
Oscar Class	1975		1980			6	8	14	140
Akula Class	1983	1999	1984		OK-650B	4	4	8	190

Year	US Sub Count	US Sub Power	US Plant Count	US Plant Power	UK Sub Count	UK Sub Power	UK Plant Count	UK Plant Power	China Sub Count	China Sub Power	China Plant Count	China Plant Power	Russia Sub Count	Russia Sub Power	Russia Plant Count	Russia Plant Power
1950	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1951	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1952	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1953	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1954	1	70	0	0	0	0	0	0	0	0	0	0	0	0	1	6
1955	1	70	0	0	0	0	0	0	0	0	0	0	0	0	1	6
1956	1	70	0	0	0	0	1	60	0	0	0	0	0	0	1	6
1957	6	292	2	92	0	0	2	120	0	0	0	0	0	0	1	6
1958	6	292	2	92	0	0	3	180	0	0	0	0	0	0	1	6
1959	18	1228	2	92	0	0	7	420	0	0	0	0	15	1130	1	6
1960	20	1279	4	479	0	0	8	480	0	0	0	0	59	5256	1	6
1961	39	2761	4	479	0	0	8	480	0	0	0	0	61	5556	1	6
1962	39	2761	6	827	0	0	13	1119	0	0	0	0	62	5706	1	6
1963	48	3463	11	1031	1	78	14	1155	0	0	0	0	65	6152	1	6
1964	58	4243	12	1049	1	78	16	1501	0	0	0	0	67	6452	3	324
1965	70	5179	12	1049	1	78	22	2965	0	0	0	0	68	6602	3	324
1966	70	5179	14	1177	3	234	24	3455	0	0	0	0	70	6902	3	324
1967	107	8065	18	2281	7	546	26	3785	0	0	0	0	122	10639	4	484
1968	107	8065	19	2336	7	546	27	4015	0	0	0	0	124	10939	4	484
1969	108	8155	22	4238	7	546	27	4015	0	0	0	0	126	11239	5	849
1970	107	8077	26	7292	10	780	27	4015	0	0	0	0	128	11507	5	849
1971	107	8077	29	9768	10	780	29	5085	0	0	0	0	137	12892	6	1266
1972	108	8242	37	16253	10	780	29	5085	0	0	0	0	140	13274	7	1683
1973	111	8737	47	25325	16	1248	29	5085	0	0	0	0	143	13588	9	3123
1974	115	9310	59	36499	16	1248	29	5085	1	40	0	0	147	14052	12	3587
1975	117	9640	65	42430	16	1248	30	5335	2	80	0	0	151	14506	14	4599
1976	121	10447	73	50276	16	1248	33	7289	2	80	0	0	156	15110	16	5611
1977	123	11051	76	53009	17	1398	34	7933	2	80	0	0	160	15574	16	5611
1978	127	11858	81	58175	18	1548	34	7933	2	80	0	0	162	15806	16	5611
1979	130	12500	81	58175	19	1698	34	7933	3	120	0	0	168	16600	18	7611
1980	134	13307	83	60407	19	1698	34	7933	4	178	0	0	173	17254	20	9211
1981	136	13879	87	64950	19	1770	34	7933	6	294	0	0	182	19848	22	10651
1982	139	14374	91	69620	20	1920	34	7933	6	294	0	0	187	20452	23	11651
1983	142	15016	94	73012	20	1920	37	9828	7	334	0	0	192	21146	24	12651
1984	146	15823	100	80711	21	2070	39	11108	7	334	0	0	197	21908	26	14091
1985	150	16630	108	90497	22	2220	40	11723	7	334	0	0	201	22372	28	17085
1986	148	16882	115	98969	23	2370	40	11723	8	392	0	0	206	23016	29	18085
1987	151	17377	123	108448	24	2520	39	11663	9	432	0	0	210	23480	30	19085
1988	153	17949	123	110940	24	2520	41	13645	9	432	0	0	215	24174	31	20085
1989	157	19013	126	114717	24	2520	41	14267	9	432	0	0	217	24360	31	20085
1990	157	19773	128	117272	24	2520	37	14027	9	432	0	0	219	24632	32	21085
1991	154	20034	126	116885	25	2670	36	13967	9	432	1	330	204	23462	32	21085
1992	156	20364	126	116885	25	2670	36	13967	10	490	1	330	196	22982	32	21085
1993	155	20781	125	117787	22	2436	31	13328	10	490	2	1314	199	23512	33	22085
1994	158	21423	120	117583	22	2436	30	13292	10	490	3	2298	200	23712	33	22085
1995	153	21528	119	117565	21	2430	29	14196	10	490	3	2298	167	20556	31	21767
1996	146	21390	120	118775	21	2430	23	12732	10	490	3	2298	135	17496	31	21767
1997	132	20298	118	118647	17	2118	21	12242	10	490	3	2298	113	16614	31	21767
1998	133	20568	114	117543	17	2118	19	11912	11	548	3	2298	113	16614	30	21607
1999	133	20568	113	117488	17	2118	18	11682	11	548	3	2298	113	16614	30	21607
2000	133	20688	112	116836	17	2118	18	11682	12	606	3	2298	114	16754	29	21242
2001	135	21108	111	116152	18	2318	18	11682	13	664	3	2298	115	16954	30	22283
2002	136	21318	110	115302	19	2518	16	10612	13	664	7	5656	115	16954	29	21866
2003	125	20592	107	113056	19	2518	16	10612	13	664	8	6384	117	17294	29	21866
2004	126	20802	103	109307	19	2518	16	10612	14	722	9	7034	117	17294	29	21866
2005	89	17961	99	106291	17	2168	16	10612	14	740	9	7034	114	16932	28	21854
2006	87.8	17808	98	105136	17.4	2265	15	10362	13.93	737.3	10	8094	108.5	16231	27	20854
2007	86.6	17655	96	103709	16.8	2161	12	8408	13.87	734.7	11	9154	104.1	15670	26	19854
2008	85.4	17502	95	102819	16.2	2058	11	7764	13.8	732	11	9154	98.6	14969	26	19854
2009	84.2	17349	94	101860	15.6	1955	11	7764	14.73	787.3	11	9154	94.13	14468	26	19854
2010	83	17196	94	101860	15	1851	11	7764	14.67	784.7	13	10900	89.67	13907	27	20854
2011	81.8	17043	94	101860	9.4	1480	11	7764	14.6	782	16	12671	84.2	13206	28	21854
2012	80.6	16890	94	101860	8.8	1377	11	7764	14.53	779.3	17	13760	79.73	12705	28	21854
2013	79.4	16737	93	100733	8.2	1273	11	7764	15.47	834.7	20	17084	75.27	12205	28	21854
2014	78.2	16584	92	99606	7.6	1170	10	7149	15.4	832	23	20351	70.8	11644	29	22854
2015	77	16431	92	99606	7	1067	10	7149	15.33	829.3	31	28645	65.33	10943	30	23739
2016	75.8	16278	93	100824	7.4	1163	9	6534	15.27	826.7	36	33678	59.87	10242	31	24919
2017	74.6	16125	92	99975	6.8	1060	9	6534	16.2	882	39	36979	56.4	9881	31	24919
2018	73.4	15972	92	99975	6.2	956.7	9	6534	16.13	879.3	46	45943	50.93	9180	33	27137
2019	72.2	15819	92	99975	5.6	853.3	9	6534	16.07	876.7	48	48779	45.47	8479	36	28388
2020	71	15666	92	99975	5	750	9	6534	16	874	50	51047	40	7778	37	29576