The Political Economy of a Soviet Military R&D Failure: Steam Power for Aviation, 1932 to 1939

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The behavior of principals and agents in the interwar Soviet economy can be studied through the failed attempt to develop a new aviation-engine technology based on the steam turbine. Some possible approaches to the evaluation of R&D failure are outlined. Soviet R&D agents competed for funding within a command system. Principals funded ventures in a context of biased information and adverse selection. In the presence of sunk costs budget constraints on individual projects were often loose, but were tightened periodically. There is evidence of rent seeking, but not that rents were distributed deliberately as political gifts to loyal agents.

The Soviet economy was managed by a vertical hierarchy in which agents supplied principals with flows of information from below and principals issued commands from above. Commands flowed downward, but the more closely we study this system the more we find that self–interested agents rarely did exactly as they were told. They ignored some orders, exceeded others, and did many things that were not ordered at all. Information flowed upwards but the most difficult problem for those who received it was to verify exactly what people were really doing when they appeared to be obeying commands.

In this article I explore the operation of the Soviet command system and the interactions among agents within it. These interactions were horizontal as well as vertical. What I mean by "horizontal" and "vertical" is this: relationships between those entitled to issue commands and those obligated to obey them occupied the vertical space, whereas horizontal relationships were formed among agents at the same vertical level. Each agent had to optimize in both dimensions simultaneously.

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We can study the process through the prism of an R&D failure. This was the Soviet attempt to create a new aviation-engine technology using steam power. It was a serious venture that consumed significant resources for a few years and provides a relatively self–contained episode for investigating the incentives and strategies that drove the allocation of scientific and technical resources.

What is an R&D failure? All research may produce new knowledge of both explicit and tacit kinds. It also generates externalities that are potentially of benefit to society; even failure may have a value if we learn from it. Here I define failure narrowly within a principal–agent framework: an R&D project fails even though it yields a return to society, if it does not generate a surplus for the funding principal from the useful application that the principal intended. Thus I will classify Soviet investment in steam power for aviation as an R&D failure even though it may have enhanced human knowledge and generated all sorts of useful spinoffs.

The economic significance of R&D failures can be considered from three perspectives. R&D failure may be analyzed within a profit-seeking framework as a cost to an economic principal, within a rent-seeking framework as consumption by an economic agent, and within a political economy framework as a channel through which a political principal may distribute rewards to loyal agents.

In considering R&D as a profit-seeking activity it is useful to distinguish the structure of competition between and within nations. In general R&D can be motivated by both "profit" and "competitive threat."[1] From a national perspective each country pursued its defense objectives as a strategic competitor in relation to other nations. Military technologies provided the means to these objectives, and investments in military R&D made the technologies more efficient. By investing in technological enhancement, each nation could expect to lower the costs of realizing its strategic goals, controlling for the R&D efforts of other states. This is the profit motive. The second motive arose from knowing that its rivals were also engaging in military R&D: the nation that fell behind might fail to maintain its strategic position and be beaten, i.e., lose ownership rights over its assets to a competitor. This motive is the competitive threat.

The dimension of competitive threat gave the process of interwar military R&D its character of a winner-takes-all race among the great powers. At the same time, competitive threat did not overwhelm the profit motive. If it had, a nation that fell behind the leader would have lost any incentive to invest in trying to come in second. In military aviation engineering we see that each great power invested substantial resources in those areas where it was not the technological leader; it was an R&D success to come in first, but it was not a failure to come in second or third; it was only a failure to come in

[1] This follows Beath, Katsoulacos, and Ulph, "Game-Theoretic Approaches."

nowhere. One reason for this is that the significant breakthroughs came too late in the war to affect the outcome. Another reason is that some of the new knowledge produced by R&D did not become common knowledge because a part was kept secret, and some of the rest remained tacit and could only be acquired through "learning by doing."[2] Thus, Germany was the first power to create jet aircraft, and was able to exploit a temporary advantage over its enemies as a result, but the British and Russians rationally maintained their efforts to come in next.

The structure of competition within each country created the same motivations in a different balance. Within the British, German, and Soviet markets for military invention individual agents also faced a profit motive and a competitive threat. Think of the returns to R&D success as partly financial and partly reputational. In terms of reputation the *only* thing that mattered was to come first: for example each country now remembers its own pioneer of the jet aviation engine, Frank Whittle, Hans von Ohain, and A. M. Liul'ka, whereas their rivals are completely forgotten. Much more than between countries, the competition within each country took the form of a race into which each rival was drawn by the chance to scoop the winnings before the others.

Other than in terms of reputation, none of the jet pioneers was allowed to make a profit from realizing their dream. In Britain the first contracts for serial production of jet engines were given to Rolls Royce, deliberately sidelining Whittle's company Power Jets, and in Germany to Junkers and BMW, favoring the rivals of Ohain's sponsor Otto Heinkel. For different reasons Soviet arrangements gave designers no expectation of a stake in the producer profits arising from their inventions. This might even have been a good thing: economic theory has shown that, when the pool of potential inventions is limited, winner-takes-all may lead rival agents to invest in R&D until all the potential gains have been competed away.[3]

The approach outlined so far treats investments in military R&D as a cost to a profit-seeking principal. Because R&D outcomes were uncertain, there were many potential projects, each with a high probability of individual failure. Principals had to be willing to fund many projects in order to ensure that at least some successful projects would be included. Thus, failed inventions were part of the cost of success.[4]

Within a rent-seeking framework, military R&D is not only an investment cost to the principal but also a source of the agent's consumption. Therefore,

[2] On tacit knowledge see MacKenzie, *Thinking Machines*, pp. 215–16; and on learning by doing Arrow, "Economic Implications."

[3] Dasgupta and Stiglitz, "Industrial Structure."

[4] Mokyr, *Lever of Riches*, pp. 176–77. Sah and Stiglitz ("Architecture of Economic Systems") have suggested that, for given incentives and a given distribution of good and bad projects, a polyarchic market system in which screening decisions are decentralized and screening intensity is endogenous should possess an advantage relative to a unified hierarchy. Therefore, a prevalence of bad projects under a hierarchy may be a cost of maintaining that hierarchy. However, this hypothesis cannot be pursued through a single case study.

military R&D may become a focus for self-interested rent seekers. Several factors encourage it: the cloak of military secrecy; relatively soft budget constraints; intrinsic uncertainty about the timescale and expected value of returns to investment that impedes selection, including the rational expectation that many projects will fail; and large information biases that impede monitoring.[5] Under these circumstances R&D agents can be expected to invest resources in lobbying to win project funding, and some of the resources they invest will be diverted from previously awarded allocations to military R&D.

Thus R&D failures may have another significance. From the point of view of the principal, R&D failures were simply part of the cost of success: some experiments fail, and failed experiments are part of the necessary background against which success is achieved. In contrast, from the point of view of rent-seeking agents, unsuccessful projects provided consumption as effectively as successful ones. From this perspective R&D failures may be a gain to the agent although a loss to the principal. Why then should agents pursue success for the principal? Agents' indifference to failure might also be strengthened if reputational capital created by past success could not be translated into higher income.

Finally, within a political-economy framework, in the presence of rent seeking a political principal such as a dictator may deliberately design the allocation system to enable transactions in the political market place, for example to distribute gifts to agents in return for loyalty.[6] Thus, in a study of Soviet regional policy James Harris has shown that Stalin used investment allocations to reward loyal agents in the regions in his struggle with the opposition in the late 1920s; during the 1930s, however, his regional agents were called to account for their uses of these resources.[7] Valery Lazarev and Paul R. Gregory have shown in a detailed study of the Soviet allocation system for motor vehicles in the 1930s that the dictator maintained a stock of vehicles in reserve for use as rewards for loyal agents.[8]

If the budgetary system is used to reward loyal agents, the effect must be that budgetary outlays will exceed an efficient level. The excess is the signal that loyalty is expected in return: if some waste did not result, those receiving the funding would have no reason to offer thanks to the government in exchange as any politician would rationally promise to undertake at least those expenditures that were efficient.[9] If the system for military procurement and R&D were used in this way, then some R&D failures might be the

[5] Kornai, "Resource–Constrained versus Demand–Constrained Systems," originated the terminology of "hard" and "soft" budget constraints; he defined the firm's budget constraint as soft when the firm is managed on the basis of a rational expectation that the state will guarantee losses and that the firm's survival and growth will be uncorrelated with its intrinsic profitability.

[6] Wintrobe, *Political Economy*, pp. 150–53.

[7] Harris, *Great Urals*.

[8] Lazarev and Gregory, "Dictators and Cars"; see also Gregory and Lazarev, "Wheels."

[9] Wintrobe, *Political Economy*, p. 31.

intended outcome of a political exchange through which both agent and principal gained: the agent gained consumption and the principal gained loyalty, which is one source of political power.

In short, the incidence of R&D failures may reflect an economic experimentation process in which a certain proportion of failures is an unintended but necessary consequence, or it may reflect an economic process in which opportunistic agents extract rents from a funding principal, or it may reflect an intention on the part of a political principal to compensate agents directly for their loyalty. To discriminate among these hypotheses in the case of Soviet military R&D requires a close study of the allocation process, and this is one purpose of the analysis that follows.

I explore this process mainly through the documentary records of the Soviet defense industry held by the Russian State Economics Archive (RGAE), supplemented by those of the Red Army held by the Russian State Military Archive (RGVA), both in Moscow. What these records make possible is a detailed analysis of Soviet research and development in terms of the problem of the principal and the strategies adopted by both principals and agents. Before the archives were available, our interpretation of the management of defense resources was based on accounts that largely denied the existence of this problem. Anodyne official histories presented a version from the standpoint of the principal, say, the Politburo and defense industry leaders, which denied that the self-interest of agent or principal might diverge from that of society. The memoirs and biographies of the agents, the producers, designers, and scientists presented a more interesting and truthful account, but from a self-interested perspective that, while honestly reporting the tensions and disagreements among principals and agents as they actually occurred, tended to attribute such problems to the principals' low education, lack of trust, excessive interference, and oppressive behavior towards those of superior culture and understanding, i.e. the agents.[10] Through the archives we can come to a more rounded understanding, observing the rules of the game and the strategies of the players from both sides.

This article is about invention, not innovation. A substantial scholarly literature has demonstrated that in Soviet industry innovation was sluggish because risks were high and rewards were meager.[11] Inventiveness, in contrast, was everywhere but, even when successful, it often did not benefit society. Joseph Berliner distinguished between activities aimed at maximizing technological objectives, which he called "mission oriented," and activities aimed at maximizing an economic surplus. He suggested that, although Soviet R&D organizations were good at accomplishing technological missions regardless of cost, they were poor at organizing

[10] See, for example, Holloway's path-breaking study of *Stalin and the Bomb*.

[11] Especially Berliner, *Innovation Decision*; Amann, Cooper, and Davies, *Technological Level*; Amann and Cooper, *Industrial Innovation*; and Amann and Cooper, *Technical Progress*.

economic activities to the benefit of society.[12] Here I hope to show that, in the Soviet economy, mission-oriented activity was also "economic activity" in the sense that everyone involved was looking for a payoff, and that the costs they were willing to incur or impose on others depended on the private stakes.[13]

PROBLEMS AND SOLUTIONS

Despite a number of major postwar studies of the comparative development of Soviet technology in various fields, a scholarly history of Soviet aircraft propulsion has yet to be written.[14] Before the revolution aviation engineering barely existed in Russia and in the early years of Soviet power it remained the "Achilles heel" of Soviet aviation.[15] The establishment of a modern industry began in the mid-1920s with the importation and adaptation of French, German, and British engines to the conditions of Soviet industry. Thereafter the Soviet Union quickly established a substantial manufacturing capacity. By the years 1936 to 1938 the total annual output of five factories had reached more than 15,000 engines of the conventional reciprocating type with an airscrew propeller, including radial and in-line, air- and water-cooled, gasoline and diesel fueled, and supercharged models.[16] However, continuously challenged by the rapidity of technological advance in other countries, the Soviet industry remained dependent on imitation and adaptation of foreign designs and did not establish an autonomous capacity for development of conventional engines.[17]

In the interwar period, aircraft performance neared the limits of the piston and propeller engine.[18] The mechanical efficiency of propellers was found to fall away beyond a point as rotation speeds increased, with the result that propeller-driven aircraft could never approach supersonic speeds or stratospheric altitudes. At full power piston engines quickly shook and ground themselves to pieces; consequently they also required frequent and intensive maintenance and had short service lives. Such limitations prompted a search in several European countries for completely new types of aviation engine based on a continuous thermal cycle giving rise to a jet reaction. In Great

[12] Berliner, *Innovation Decision,* pp. 506–09.

[13] Applied more generally this approach may eventually lead to new comparisons with military-industrial planning and procurement processes in market economies, including the United States, but the necessary analysis is still at a preliminary stage. See Harrison, "Soviet Industry"; and Gregory, "Why Was Soviet Defense Planning?"

[14] Sutton, *Western Technology*; Amann, Cooper, and Davies, *Technological Level*; Hanson, *Trade*; Amann and Cooper, *Industrial Innovation*; Amann and Cooper, *Technical Progress*; and Albrecht, *Soviet Armaments Industry*, investigate Soviet industrial and military-technical progress more generally defined.

[15] Sobolev, *Nemetskii sled*, p. 30.

[16] For serial production figures see Kostyrchenko, "Organizatsiia," p. 429.

[17] Albrecht, *Soviet Armaments Industry*, pp. 28–32.

[18] Grigor'ev, "Aviatsionnoe motorostroenie," p. 189.

Britain, Germany, and the Soviet Union much effort was invested in two alternatives: the rocket motor and the jet engine.[19]

The rocket principle had been well understood for hundreds of years, and European armies had used small, solid-fueled rockets on the battlefield since the Napoleonic era. The new fuels and heat-resistant materials being developed in the early twentieth century promised significant applications for the rocket principle in aircraft propulsion. However, to create a primary rocket motor for aviation implied a design of unprecedented size and complexity by interwar standards, depending on more powerful liquid fuels and substantial further advances in material and fuel sciences and control systems. At the end of the development process lay apparatuses that could attain extraordinary speeds and limitless altitudes but consumed fuel at rates that limited powered flight to a few minutes' duration.

The concept of the jet engine was of more recent origin. It overcame the restricted flight duration of the rocket by breathing oxygen from the air, but this limited its use to atmospheric flight. Earlier designs could not provide a primary power plant because they could not be ignited unless the aircraft was already moving at flight speed. Later designs such as the turbojet eliminated this defect at the cost of added complexity including moving parts rotating at very high speeds and temperatures; these could not be brought to realization without still greater advances on interwar benchmarks in terms of heat-resistant alloys, fuels, and the control of combustion.

Hindsight tells us that by the end of World War II the turbojet would solve the problem of high-speed, high-altitude aviation. Liquid-fueled rocketry, while not the answer for aviation, would solve other problems of strategic bombardment and space travel. During the interwar period this outcome was not yet clear and several avenues that would later be seen as stopgaps or failures were also explored. Among these were various attempts to build a propulsion unit based on the steam turbine.

The basic scheme is shown in Figure 1. It involved an oil-fired boiler to create steam; expansion of the steam in a turbine converted part of its thermal energy into kinetic energy, initially in the form of the torque required to rotate an airscrew propeller; the propeller drove an airstream backwards and the aircraft forwards. As the aircraft in flight could not replace its water, the steam was passed through a condenser and returned to the boiler in a closed circuit.

Figure 2 arranges the spectrum of modern aviation engines in two dimensions. Along the vertical axis the technologies of more recent development that make use of a continuous thermal cycle are demarcated from the tradi-

[19] Soviet rocketry before and during World War II has been investigated by Ordway and Sharpe, *Rocket Team*; Holloway, "Battle Tanks"; Siddiqi, *Challenge*; and, with the benefit of new archival documentation, Harrison, "New Postwar Branches." On the early development of the Soviet jet aviation engine see Harrison, "Soviet Market."

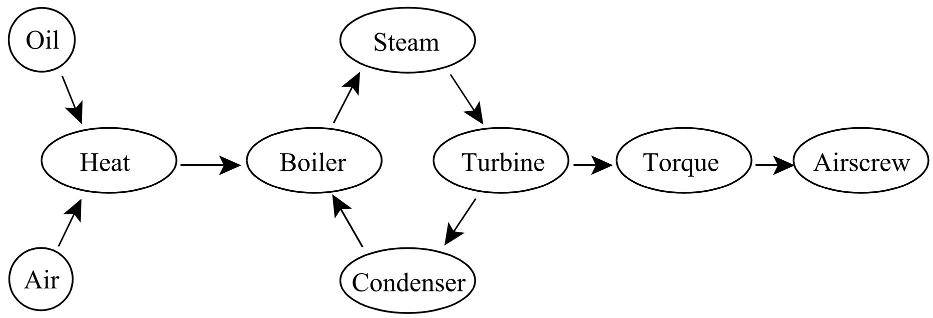

FIGURE 1
THE STEAM TURBINE IN AN AVIATION PROPULSION UNIT

tional technology that relied on the intermittent action of reciprocating pistons. Along the horizontal axis the proportion of the energy that is delivered in the form of a jet stream or thrust, rather than of torque to a propeller or turbine, rises from zero to infinity.

The steam turbine lies at the most conservative extreme of the range of continuous thermal cycle engines, in that it aimed to deliver torque more efficiently and reliably rather than replace torque by thrust. This meant that the steam turbine, even if it worked, would never give access to supersonic speeds or stratospheric altitudes. Its main advantage lay in offering to replace the reciprocating engine with a familiar continuous-cycle technology that operated quietly and reliably for long periods at moderate temperatures and rates of rotation, with less destructive vibration and fire hazard, using materials that were already available and cheaper fuels.[20]

Only hindsight makes the concept of steam aircraft appear surprising. Between the development of the steam locomotive and the advent of the light gasoline engine there were many projects for steam-powered flight. Charles Parsons, who invented the steam turbine in 1884, successfully tested a model steam airplane in 1893.[21] In the interwar period steam turbines were widely used in naval propulsion, their other main use being in electric power generation. Historically the gas turbine came after the steam turbine and arose from the latter, so it was the steam turbine that was already the more proven technology.[22] After World War I research on these lines in the United States was resumed by the Navy Department Bureau of Engineering in 1922.[23] Others followed not only in America but also in Britain, France, and Germany. In the 1930s, however, as will become apparent, it seems likely on present information that more aviation steam power projects were pursued in the Soviet Union than in the rest of the world put together.

[20] For example Knörnschild, "Dampftriebwerke," p. 367. I thank Jean Vezina for this reference and Godfrey Carr for his translation of it from German.
[21] Gibbs-Smith, *Aviation*, p. 70 and more generally pp. 59–68.
[22] Voronkov, "Teoriia," p. 115.
[23] Knörnschild, "Dampftriebwerke," p. 369.

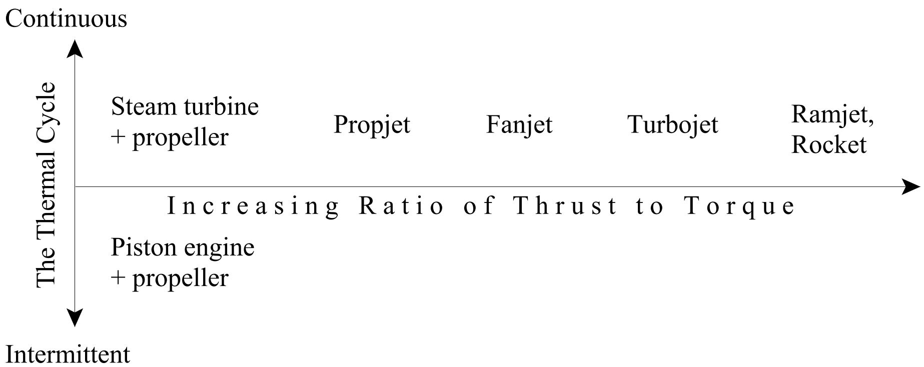

FIGURE 2
WHERE THE STEAM TURBINE ENGINE FITS

If steam turbines replaced the reciprocating engine at sea, why did this not happen in the air as well? The main problem was that existing land- and ship-based applications of the steam turbine were based on ratios of power to weight and volume that were too low to take to the air. Aviation applications required not only efficient boilers but also bulky condensers to convert steam back to water; these could scarcely be accommodated within an airframe light enough to be lifted into the air by the power that the turbine would develop.[24] Improving power relative to the mass of the engine was therefore the main focus of aviation-related development efforts. This meant primarily increasing the fuel efficiency of the boiler, and reducing the volume of the condenser and the mass of the circulating medium.

SCALE AND SCOPE

Scale

Table 1 provides an overview of the main Soviet R&D projects in aviation steam turbines from 1932 to 1939. It is compiled from plans, reports, and memoranda of the commissariats of defense, heavy industry, the defense industry, and the aircraft industry. The table shows that in the prewar years there were 11 major projects; taking into account the life of each venture, the total of activity amounted to 34 project-years. The eleven projects involved eleven research establishments, but the association between projects and establishments was less tidy than this would suggest since some designers had more than one institutional affiliation both through time and contemporaneously. There were five main funding interests: the Red Army air force, the civil aviation authority, the Academy of Sciences, the aircraft

[24] Liul'ka and Kuvshinnikov, "K istorii," p. 88.

TABLE 1
MAJOR SOVIET PROJECTS FOR AVIATION STEAM TURBINES, BY ESTABLISHMENT, 1932 TO 1939

	1932	1933	1934	1935	1936	1937	1938	1939
KhAI	Tsvetkov 15,000hp turbine———							
	Tsvetkov "air-naval" PT-6 (6,000hp) ———|			PT-6 (3,000hp)———|			
NII GVF	PT-3 (3,000hp) "air–naval" steam turbine ———							
VVA	Aksiutin PT-1 (1,500/2,500hp) turbine (continued at SKB and Energeticheskii institut)							
SKB	Sinev turbine					Sinev 1,600/2,500hp turbine———		
SKB and EI						Aksiutin turbine (from VVA)———		
KB–2		Kozhevnikov 400hp gas-steam turbine———						
VTI				"Air-naval" 1,000hp turbine				
VTI and MAI						Przheslavskii 2,000hp binary-cycle steam turbine———		
TsKTI						Hüttner turbine	VT-1, VTK-100 (100hp), and VTK-3000 (3,000hp) turbines	PT-1M (2,000hp) and VTK-300 (100hp) turbines
Zavod no. 18						Dybskii-Udod gas-steam turbine ——		
TsIAM								1,600hp, single-, and binary-cycle turbines

Key to Design Establishments:
KhAI = Khar'kovskii Aviatsionnyi institut NKTP-NKOP-NKAP [Kharkov Aviation Institute of the People's Commissariat of Heavy Industry, later the Defense Industry, later the Aircraft Industry]
NII GVF = Nauchno-Issledovatel'skii institut Grazhdansko-Vozdushnogo Flota GUGVF SNK [Research Institute of the Civil Air Fleet of the Chief Administration of the Civil Air Fleet of the Council of People's Commissars]
VVA = Voenno-Vozdushnaia Akademiia RKKA [Air Force Academy of the Workers' and Peasants' Red Army]

TABLE 1 — continued

SKB, later SKB-1 = Spetsial'noe Konstruktorskoe biuro Pervogo Glavnogo upravleniia NKOP [Special-purpose Design Bureau of the First Chief Administration of the People's Commissariat of the Defense Industry]

EI = Energeticheskii institut AN SSSR [Energy Institute of the USSR Academy of Sciences]

KB-2 = Konstruktorskoe biuro no. 2 UVI RKKA [design bureau no. 2 of the Administration of Military Inventions of the Workers' and Peasants' Red Army, Leningrad]

VTI = Vsesoiuznyi Teplotekhnicheskii institut im. Dzerzhinskogo NKTP [Dzerzhinskii All-Union Thermal-Technical Institute of the Electricity Supply Industry Administration of the People's Commissariat of Heavy Industry]

MAI = Moskovskii Aviatsionnyi institut NKTP-NKOP-NKAP [Moscow Aviation Institute of the People's Commissariat of Heavy Industry, later the Defense Industry, later the Aircraft Industry]

TsKTI = Tsentral'nyi Kotlo-turbinnyi institut Energoproma NKTP [Central Boiler and Turbine Institute of the Electricity Supply Industry Administration of the People's Commissariat of Heavy Industry, Leningrad]

Zavod no. 18 = zavod no. 18 NKOP [factory no. 18 of the People's Commissariat of the Defense Industry, later the Aircraft Industry]

TsIAM = Tsentral'nyi Institut Aviationnogo Motorostroeniia NKTP-NKOP-NKAP [Central Institute for Aeroengine-Building of the People's Commissariat of Heavy Industry, later the Defense Industry, later the Aircraft Industry]

Sources: The supporting documentation comprises plans, reports, and memoranda of the People's Commissariats of Defense, Heavy Industry, the Defense Industry, and the Aircraft Industry: RGAE, 8044/1/994, ff. 21–23; 8328/1/696, f. 25; 8328/1/824, ff. 1–50; 8328/1/919, f. 84; 8328/1/992, ff. 6–7; 8328/1/996, ff. 16–18 and 22–23ob. RGVA, 4/14/2800, f. 4; 34272/1/167, ff. 23–24, 47–55, and 102–119. See also Rodionov, *Aviation*, 1932 under the month of September, 17 September, and 31 December; 1933 under 10 February and 8, 21, and 23 March; and 1934 under 3 and 14 July. Other steam power aeroengine projects not considered here include work on the Besler engine, discussed in the Appendix, at the Moscow Aviation Institute (MAI), and a plan, evidently soon abandoned, to build a steam-turbine supercharger for a reciprocating aeroengine in 1932–3 at the Khar'kov Aviation Institute (KhAI) and under the Red Army Bureau of New Designs (BNK); on the latter see Rodionov, *Aviation,* 1932 under September (Sovnarkom decree on the construction of steam turbine engines), and 1933 under 17 January (Unshlikht to the Council of Labor and Defense) and 23 March (Almazov to Gosplan).

industry, and the electricity generation industry.[25] Four designers in three urban centers accounted for three fifths of the total activity: S. A. Aksiutin and N. M. Sinev in Moscow, P. L. Kozhevnikov in Leningrad, and V. T. Tsvetkov in Khar'kov.

The time profile of these projects is illustrated in Table 2 and Figure 3. Officially work began in 1932. From then to the end of 1937 ten projects were initiated. Four of these had been curtailed already by the end of 1936, so the number of major projects in progress peaked at the end of 1937 at six. Of the six, five were cancelled during 1938 and, although one more was begun during 1939, bringing the total to 11, all had been abandoned by 1940.

Did the Soviet effort represent a significant commitment of national resources? Based on the information available at present, the answer appears

[25] The involvement of the electricity generation industry might be construed as an attempt to extract rents from new uses for an existing technology in which it had a vested interest. In a similar case Henning and Trace, "Britain," p. 385, attribute the British interwar slowness to adopt diesel engines for marine propulsion in preference to steam turbines partly to "the over-optimistic performance claims by builders of steam-turbine machinery." I thank Stephen Broadberry for this reference. In the Soviet case aviation specialists came to see the electricity supply engineers as hostile rivals; for evidence see note 60.

TABLE 2
THE NUMBER OF MAJOR SOVIET PROJECTS FOR AVIATION ENGINES BASED ON JET PROPULSION AND TURBINES, 1 JANUARY 1932 TO 30 JUNE 1941

	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941
Steam Turbines										
1 In progress at start of year	0	3	4	4	3	2	6	1	—	—
2 Starting during year	4	1	0	1	0	4	0	1	—	—
3 Continuing during year	4	4	4	5	3	6	6	2	—	—
4 Discontinued by end of year	–1	0	0	–2	–1	0	–5	–2	—	—
5 In progress at end of year	3	4	4	3	2	6	1	0	—	—
Gas Turbines, Jets, and Rockets										
1 In progress at start of year	0	1	1	1	1	3	3	3	6	4
2 Starting during year	2	0	1	0	2	1	1	5	0	3
3 Continuing during year	2	1	2	1	3	4	4	8	6	7
4 Discontinued by end of year	–1	0	–1	0	0	–1	–1	–2	–2	0
5 In progress at end of year	1	1	1	1	3	3	3	6	4	7

Note: I count as one "major project" work that is continued in one establishment from year to year even though the particular objects may vary, and also work that is continued on a particular object from year to year by one designer even though the sponsoring establishment may change. Row 1 equals row 5 in the preceding year; row 5 is the sum of rows 4 and 3; row 3 is the sum of rows 2 and 1.
Sources. This table is adapted from Harrison, "Market," table 2; for steam turbines specifically, see table 1.

to be no. At the end of 1937, acting director Sinev of the special-purpose design bureau (SKB) of the commissariat of the defense industry put the total of sunk costs of the various steam turbine projects so far at 20 million rubles over five and a half years, i.e., not more than four million rubles per year.[26] On the basis of an annual average wage for that period of 3,000 rubles, four million rubles would also represent the direct-plus-indirect employment of up to 1,300 public-sector workers. Included in this total were a few scientists and designers who were more highly paid and were a particularly scarce resource, but even 100 such specialists would have represented no more than one per thousand of the Soviet Union's stock of "scientific workers" in 1940.[27]

Although insubstantial in absolute terms, the Soviet interwar effort in the direction of aviation steam power represented a measurable proportion of overall Soviet military R&D resources; these are known only for 1936 and 1937, and were as follows (in million rubles): the 1936 plan was 119, actual was 88; the 1937 plan was 136, actual was 67.[28] Thus four million rubles a year represented 3 percent of resources budgeted for military R&D in these years, and 5 percent of resources used.

What is also to the point is that Soviet funding of steam power plants for aviation probably exceeded that channeled into the much more famous

[26] RGAE, *fond* 8328, *opis'* 1, *delo* 992, folio 15 (hereafter 8328/1/992, f. 15) (19 December 1937).
[27] There were 98,300 "scientific workers" in the Soviet Union in 1940 according to Goskomstat, *Narodnoe khoziaistvo*, p. 64.
[28] Harrison and Davies, "Soviet Military-Economic Effort," p. 387. These figures in turn represented less than 2 percent of total military equipment orders.

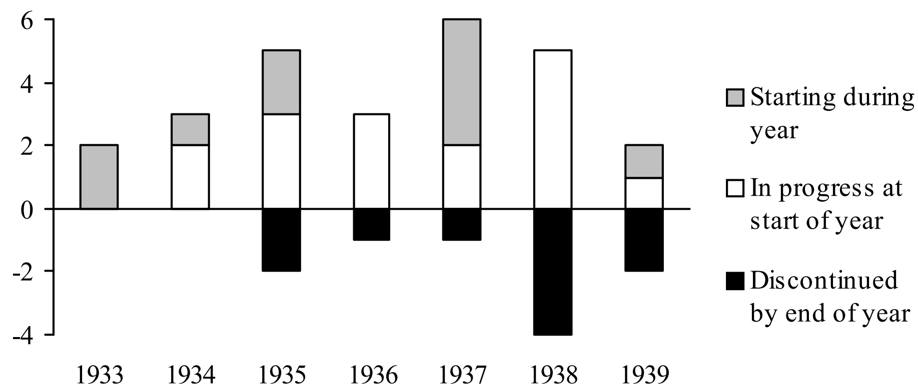

FIGURE 3
SOVIET AVIATION-RELATED R&D IN STEAM TURBINES, 1932–1939
(numbers of major projets)

Source: Calculated from Table 2.

projects for gas turbines, jet engines, and rockets. Table 2 shows that in every year between 1932 and 1938 at least as many and usually more steam turbine projects were in progress than the number of jet propulsion projects. Only in 1939 did efforts in jet propulsion begin to overshadow the steam turbine projects as the cull of the latter came to an end. Consequently, as Figure 4 shows, the cumulative investment of Soviet R&D resources in steam turbines, measured in major project-years, was overtaken by that in jet propulsion only in 1941.

How did the scale of Soviet research compare with efforts being made in other countries? Table 3 shows that there were eight other major steam-turbine ventures between the wars: three in the United States, three in Germany, and one each in Britain and France. The Besler engine is also worthy of note; although not a turbine, and unsuitable for scaling up to the much larger capacities sought by Soviet designers, it was the first and only steam engine to succeed in powering piloted flight. Besler, having acquired Doble Steam Motors in 1931, had developed a compact 150 horsepower steam reciprocating engine for use in rail and road transport. Installed in a light aircraft it took to the air on 12 April 1933, and this attracted the attention of the Soviet government; further information is given in the Appendix. Leaving the Besler engine to one side, it would appear that at this time there were fewer ventures in the whole of the rest of the world than in the Soviet Union.

Scope and Performance

Despite a common basic inspiration there was considerable technical variation among steam turbine designs. One variant with British, German,

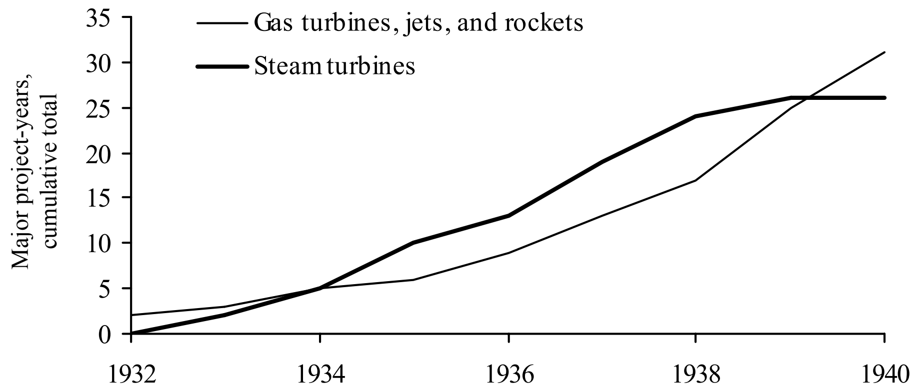

FIGURE 4
SOVIET AVIATION-RELATED R&D IN STEAM TURBINES VERSUS GAS TURBINES, JETS, AND ROCKETS, 1931–1941: CUMULATIVE INVESTMENTS IN MAJOR PROJECT-YEARS

Source: Calculated from Table 2.

and Soviet derivatives was the Hüttner turbine; this replaced the conventional static boiler which blew hot gas past water pipes with a rotating boiler that moved U-shaped water pipes at high speed through the hot gas while the turbine was rotated in the opposite direction. Other refinements could include using a multi-stage turbine to convert more of the overall steam pressure drop into useful energy; expanding the boiler's exhaust gases in a gas turbine to supercharge the boiler itself or to supplement the torque delivered to the propeller; and using the heat otherwise lost from the condensing steam to expand the cooling air in such a way as to add to the overall thrust. The "gas-steam" apparatuses of Kozhevnikov and the Dybskii-Udod partnership evidently made use of the boiler's exhaust gases in an auxiliary turbine. Przheslavskii's "binary-cycle" turbine used a high-temperature liquid, probably mercury, in a preliminary stage to a water boiler so as to economize on the mass of the circulating medium and reduce specific fuel consumption.[29]

Soviet design capacities ranged from a few hundred horsepower to the 15,000 horsepower rating of Tsvetkov's first monster that was never built. By comparison, the largest reciprocating aviation engines in serial production in the Soviet Union and elsewhere at the end of the 1930s somewhat exceeded 1,000 horsepower.

The performance characteristics that mattered most were specific weight and specific fuel consumption, both measured relative to capacity. These are

[29] The principle of the mercury boiler, first applied in the United States by General Electric in 1914, is evaluated by Stodola, *Steam and Gas Turbines*, pp. 1313–16. On the advantages see Knörnschild, "Dampftriebwerke," p. 367.

TABLE 3
DESIGNS FOR AVIATION STEAM TURBINES IN THE REST OF THE WORLD, 1922–1942

Corporation or Designer	Country	Begun or in Progress	Capacity (hp)	Specific Weight (kg / hp)	Specific Fuel Consumption, (g / hp / hour)
Navy Department Bureau of Engineering	United States	1922	—	3.0	500[a]
Great Lakes Aircraft and General Electric Corporations	United States	1932 or earlier	2×1,150	1.44[b]	300[b]
Hüttner[c]	Germany	1937 or earlier	—	1.0	280–300
Vorkauf[c]	Germany	1937 or earlier	—[d]	—	—
Wagner	Germany	1937 or earlier	2×3,000	1.2	220
Aero-Turbines[c]	United Kingdom	1938	2,000	0.9	160
William Brobeck[e]	United States	1941 or earlier	1,000	0.9	—
Béchard[c]	France	1941 or earlier	—	—	—

[a] This figure is based on Knörnschild's statement that a specific fuel consumption of 250 grams per horse power per hour would be possible with a 100 percent improvement in weight and consumption.
[b] These figures, calculated from imperial units given by Collina, are preferred to slightly lower figures of 1.33 kilograms per horsepower and 270 grams per horsepower per hour from Knörnschild.
[c] Hüttner and Béchard manufactured boilers that rotated in the opposite direction to the turbine; the Aero-Turbines design was based on a Hüttner turbine.
[d] A capacity figure of 650kW is given by Knörnschild.
[e] William Brobeck was formerly chief engineer of the Besler Corporation.
Sources. The fullest survey is provided by Knörnschild, "Dampftriebwerke"; the subsequent wartime survey by Smith, *Gas Turbines*, pp. 36–40, appears to take much of its information from Knörnschild. Collina, "Steam Power Plant," had previously placed details of the Great Lakes Aircraft-GEC venture in the public domain; this is another reference for which I thank Jean Vezina. I omit from the table three other steam power projects as not turbines or not prime movers: Knörnschild counts the Besler engine of 1932, further described in the Appendix; Smith lists a Breguet Aviation project of 1942 to build a steam powered supercharger for a jet engine, and also a United Aircraft design in the name of the helicopter prioneer Igor Sikorsky and others to build a steam turbocompressor onto a conventional radial engine for added thrust. A Soviet memorandum of 28 February 1937 (RGAE, 8328/1/919, f. 77) lists seven foreign steam turbine ventures by AEG, Wagner, Hüttner, Vorkauf, Besler, Doble, and General Electric-Great Lakes Aircraft, but without giving any details; thus it correctly identifies four that were included subsequently in Knörnschild's survey, but wrongly counts Besler and Doble which was a single venture and not a turbine. Despite the evidence of this memorandum I omit AEG from the table since no details are provided, there is no corroboration in other sources, and the accuracy of the Soviet information about other foreign ventures appears to have been poor.

not always reported in the documentation; Tables 3 and 4 show available figures for Western and Soviet designs respectively. The typical Soviet design reported in Table 4 proposed a 1,000 to 3,000 horsepower engine with a specific weight of 1 kilogram per horsepower and specific fuel consumption around 300 grams per horsepower per hour of operation; some were better and some were substantially worse. This pattern was similar to the variation among the Western designs listed in Table 3.

The specific weight of the Soviet steam turbines was generally not as good as that of contemporary piston engines. Thus the design weight of one piston engine that was mass-produced in very large numbers in the mid-

TABLE 4

SOVIET DESIGNS FOR AVIATION STEAM TURBINES: TECHNICAL CHARACTERISTICS

Design Establishment	Designer	Model	Capacity (hp)	Weight (kg)	Specific Weight, (kg / hp)	Specific Fuel Consumption (g / hp / hour)
KhAI	Tsvetkov	—	15,000	16,500	—	—
KhAI	Tsvetkov	PT-6	6,000 reduced to 3,000	9,600 reduced to 3,000	—	—
NII GVF	—	PT-3	3,000	3,000	—	—
TsKTI	—	PT-1M	2,000	—	1.0	300
SKB	Sinev	—	1,600 increased to 2,500	—	2.5	350–400
VVA-SKB-EI	Aksiutin	PT-1	1,500 increased to 2,500	—	1.0	220
VTI	—	"Air–naval"	1,000	1,000	—	—
KB-2	Kozhevnikov	—	400	—	0.65[a]	—

[a] This figure excludes the weight of a gas turbocharger.
Sources: As for Table 1.

1930s, the Mikulin M-34, was 0.8 kilograms per horsepower.[30] Moreover, the specific weight of piston engines was falling. The M-34 and Klimov M-105, the Wright Cyclone and its Soviet derivative the M-25, and the Rolls Royce Merlin, all dropped to 0.6 to 0.7 kilograms per horsepower in their last versions of the prewar period.[31]

Specific fuel consumption can also be compared. In the mid-1930s the design consumption of the M-34 in its RN or FN version was 255 grams of aviation spirit per horsepower per hour.[32] The TB-7 heavy bomber of 1936, an aircraft that some designers intended for a steam turbine, provides a cross-check from practical aviation: equipped with four M-34FRN piston engines its operating fuel consumption was roughly 300 grams per horsepower per hour.[33] Tables 3 and 4 suggest that some more fuel-efficient steam turbines were competitive with this. Direct comparison is complicated by the fact that piston engines burned high-octane petroleum rather than the low-grade fuel oil used by a steam boiler.[34] This meant that the steam turbine engines used a fuel that was much cheaper and more readily available than

[30] Rodionov, *Aviation*, 1934 under 3 July.

[31] Grigor'ev, "Aviatsionnoe motorostroenie," pp. 86, 90, and 93.

[32] Rodionov, *Aviation*, 1934 under 14 July and 1936 under 5 July.

[33] This figure is obtained as follows. The maximum range and speed of the TB-7 in 1936 were 3,000 kilometers and 403 kilometers per hour at an altitude of 8,000 meters, but no aircraft could achieve both at the same time; a cruising speed of 350kph would suggest a maximum flying time of 8 hours 35 minutes. Its four M-34FRN engines totaled 3,600 nominal horse power but for cruising speed say 3,200hp, making a maximum flight total of just over 27,400 horsepower hours. The TB-7 carried 8,250 kilograms of fuel, making roughly 300 grams of fuel consumed per horsepower per hour. Technical details are from Gunston, *Osprey Encyclopedia*, pp. 280–81. Thanks to Keith Dexter for advice.

[34] According to Jasny, *Soviet Prices*, pp. 151–52, the official wholesale prices of fuel oil in Leningrad and of grade 2 motor petroleum in Moscow in 1937 were 155 and 900 rubles per ton respectively.

for existing engines, so regardless of specific fuel consumption they offered immediate gains in operating costs.

Ultimately, lower running costs did not compensate for the sheer mass of steam turbine engines, including the mass of fuel. The ruble cost of fuel required was a less important limit on performance than its weight. A TB-7 with its fuselage rearranged to accommodate boiler and turbine and its wings filled by condensers had little space remaining for fuel, crew, or payload.

PROJECT FINANCE

Rationing, Rivalry, and Budget Constraints

What limited Soviet outlays on steam propulsion R&D? Stalin's Politburo set cash limits on ministerial budgets from year to year, but detailed allocation was delegated to officials at or below the level of minister. The main problem these officials faced was technological uncertainty: R&D agents presented them with many proposals for long-term projects, one of which would eventually solve the problem of aviation propulsion for the next half century, but no one knew which one. Rationing was an appropriate response. Funding was rationed across new projects, and was also rationed through time for established projects. As a result, R&D agents competed for both initial funding and subsequent refinancing. Making limited allocations to many projects permitted funding principals to exploit the rivalry of the agents and, by monitoring the progress of competing projects, to use each to provide information about the others and thus learn about their true worth. And by rationing funding through time principals could monitor the cumulative progress of each project towards its goal so that subsequent refinancing decisions could be taken in the light of more information than was available initially.

Such competition was not normal elsewhere in Soviet industry. In civilian branches funding principals and agents were more likely to form closed bilateral relationships. This did not rule out parallel projects or duplication of work, but it did ensure that organizations working on related issues did not necessarily compete with each other and might not even be aware of each others' work; thus producer interests took priority over the consumer.[35] In the defense industry, in contrast, the government promoted the interests of a powerful consumer, the defense ministry, by assigning similar specifications to rival design bureaus; the latter were then forced to compete for their designs to be adopted. This practice was pioneered before the war in aircraft and aviation-engine development.[36] As will become apparent, however, the intensity of competition was varied through time. Indeed, after

[35] Berliner, *Innovation Decision*, pp. 120–27

[36] Holloway, "Innovation," pp. 317–19.

World War II it was suggested to Stalin that the Soviet Union was lagging in aircraft and aviation engines because relationships between the air force and the leading aircraft design bureaus had been or had become too cosy, enabling favored designers to establish monopolies and relax the pace of development. This was one source of the "aviators' affair" of 1946 in which leaders of the air force and aircraft industry were arrested and imprisoned.[37]

By rationing limited finance across competing projects and through time the principal could exploit agents' rivalry, but rationing also carried important costs. Rationing through time had the effect of softening budget constraints on individual projects because, in the presence of sunk costs, a project could attract refinancing even when it was known to be bad. Because some costs were already sunk, it could still be efficient for both the funding principal and the R&D agent to continue a project that the principal would have preferred not to finance in the first place.[38] Rationing across projects brought the danger of a fragmentation of effort in many rival projects, all underfunded. Both types of rationing invited agents to invest resources in lobbying to soften constraints and to use the argument that costs had already been sunk as an argument for project continuation.

Financial constraints on projects in progress therefore tended to become soft, and occasionally this became explicit. The technical council of the chief administration for the aircraft industry met in August 1936 to review the development of a number of steam turbine projects. The deputy minister for heavy industry Mikhail Kaganovich presided.[39] In the passage below he refers to his boss, minister for heavy industry G. K. "Sergo" Ordzhonikidze, a member of Stalin's inner team. One of the designers present reported: "they told me [that] to carry out the testing of the turbine in our factory funds of the order of a million rubles [were] needed." Kaganovich interrupted: "I can provide it." Kaganovich told another designer to proceed if he could to a flight test: "Whatever it costs I'll pay." He summed up: [40]

> I am not so poor, we have money in the sums that are needed, the boss is not hoarding it, comrade Ordzhonikidze says to take what you need.

What were the consequences of a soft budget constraint? The soft budget constraint might seem like a good thing for technical progress at first sight because the chances of successful invention would appear to increase with the number of generously funded projects. However, a soft budget constraint probably also encouraged adverse behavioral responses. Philip Hanson and

[37] Bystrova, *Voenno-promyshlennyi kompleks,* pp. 320–21. This was not the only source of the purge; according to Pikhoia, *Sovetskii soiuz*, pp. 45–47, Stalin also designed it to undermine the position of the leader of the war effort Marshal G. K. Zhukov.

[38] Dewatripont and Maskin, "Credit," propose centralized credit and sunk costs as the general explanation of soft budget constraints and shortage phenomena in a socialist economy.

[39] This was the brother of the more famous Politburo member and Stalin's deputy Lazar Kaganovich.

[40] RGAE, 8328/1/824, ff. 40, 51, and 52ob (22 August 1936).

Keith Pavitt have noted a tendency of government-funded R&D to generate "too few technical alternatives"; this is because, when budget constraints are soft, R&D agents display insufficient care in coming to conclusions. They "do not apply the normal, prudent practice of commercial firms in carefully exploring technical alternatives in order to reduce technical and commercial uncertainties. Instead, they tend to follow a high risk strategy of premature commitment to the full scale commercial development of a particular technical configuration, before the reduction of key technical and commercial uncertainties."[41] In short, uncertain outcomes are not a good reason to throw money at a problem.

Rationing and soft budget constraints help explain an institutional cycle that accompanied Soviet progress in new aviation-engineering technologies in the interwar years.[42] The first phase was one of exploration. For the first time the principal defined the mission and agents formed a lobby. As a result cash was allocated and initial funding was dispersed among agents. With first results, existing projects were refinanced and further projects were designated. At a certain point the principal lost patience with rising expenses and lack of results, and declared a need to concentrate efforts and focus them more narrowly. For example in August 1936 Kaganovich wrote to the Council for Labor and Defense with Ordzhonikidze's support to unify all work on steam and gas turbines under his chief administration for the aircraft industry.[43]

Exploration now gave way to rationalization. In the rationalization phase funding was removed from those projects judged less successful, which were terminated, and was concentrated on fewer projects reflecting more limited priorities. Agents responded both defensively and aggressively. Then the cycle was repeated because in the course of rationalization the principal made mistakes, curtailing some good projects as well as bad ones. Therefore, rationalization was often temporary because agents would eventually mount challenges to central priorities and organizational monopolies from below and exploration would begin again. This was a resilient cycle; it could only be curtailed by force.

The Financing Decision

On the demand side of the financing decision were the *funding principals*. The fundholder and the funding department were not necessarily the same. The *fundholder*, the legal owner of the R&D assets, was usually an indus-

[41] Hanson and Pavitt, *Comparative Economics*, p. 46. Why may hierarchies accept more bad projects than a market system? Hanson and Pavitt's reasoning proposes that a hierarchy generates specific incentives and is therefore made on different grounds from that of comparative "architecture" proposed by Sah and Stiglitz, "Architecture."

[42] See also Harrison, "Soviet Market."

[43] Rodionov, *Aviation*, 1936 under 3 August. Evidently, this request failed.

trial ministry, but the Red Army also maintained its own R&D establishments. The *funding department* paid for R&D services. Some centralized orders were paid directly out of the USSR state budget. In addition, budgetary institutions such as the defense commissariat were entitled to enter into decentralized contracts with industrial institutes and design bureaus for R&D services. Finally, the fundholder could also commission in-house research from its own establishments.

Both fundholders and funding departments operated within a framework of strategic directives that were issued from time to time by high-level government committees: the Council for Labor and Defense or the executive subcommittee of the Council of People's Commissars responsible for defense matters. In practice, regardless of the formal issuing authority, Stalin personally made such decisions in secret consultation with a varying circle of individual Politburo members, usually after receiving representations from the funding department and fundholder.[44]

Within this framework both funding departments and fundholders formulated operational plans. The most important planning horizon was annual. The Red Army had an annual plan for the development of military inventions some of which it funded directly through its own R&D establishments; it contracted the rest out to other organizations. Industrial ministries, including the branches of the defense industry, had their own R&D plans. This included the aircraft industry's annual plan for aviation-engine research and experimentation to be carried out by its own institutes and bureaus, part of which was made up by contracts accepted from the Red Army.

How did projects win a place in the plan? There was a variety of routes, but their common feature was that the initiative lay with the designer. This was not a process whereby an all-seeing and all-knowing planner identified needs from above, sought out designers, and put them together with resources to meet the needs identified. Rather, proposals came first from below. Established designers continually brought proposals for radical innovations to the attention of funding principals; it was their job to do so. For example, here is deputy minister for the aircraft industry M.M. Kaganovich again in August 1936:

> Three years ago comrade Tsvetkov came to me and proposed making such a turbine, I went to the boss, the people's commissar signed a decree to the effect that, in urgent order, under personal responsibility, [inaudible] to build a turbine . . . .[45]

Successful proposals required investments in lobbying. Such investments could bring not only success for individual proposals but also long-term privileged relationships with government officials responsible for funding. To win support for their projects and adoption of their designs, designers

[44] Rees, "Leaders."
[45] RGAE, 8328/1/824, f. 35 (22 August 1936).

had to be "heterogeneous engineers" capable of reshaping organizational as well as technological constraints.[46] To create a demand for new designs they had to build coalitions with soldiers or industrialists to overcome producer and consumer interests vested in markets for products that already existed.

Much has been written about Marshal M. N. Tukhachevskii, Red Army chief of armament from 1931 to 1936, as the military patron of jet propulsion in the Soviet Union between the wars. In November 1929 the post of chief of armament of the Red Army was created to help carry through its equipment modernization. The first chief of armament was Army Commander I. P. Uborevich, followed in 1931 by Army Commander, later Marshal, M. N. Tukhachevskii.[47] Among the departments reporting to the chief of armament was an administration for military inventions. In 1936 the post of chief of armament was abolished, its place taken by a chief administration for supply of weapons and equipment, and under the latter a department for inventions.[48]

An assiduous networker, Tukhachevskii used his oversight of military R&D to forge exclusive links with designers and acquire a monopoly of jet propulsion development for both artillery and aviation as both funding principal and fundholder. In this ambition he was never successful. It is notable that the first projects in steam propulsion were also sponsored by establishments of the Red Army, including KB-2 which was directly under Tukhachevskii's control as chief of armament at the time.

Which problem was more important for the principal: was it to *promote*, or to *limit* the number of projects involving steam propulsion? The funding principals struggled continually to limit and constrain initiatives and proposals from below, which were diverse and flowed from many sources, and were much more numerous than initiatives from above. As a result, R&D projects had a tendency to proliferate. Reports and resolutions prescribing the consolidation or cancellation of existing rival projects greatly outweighed the number of decisions authorizing new ones.

Refinancing

When projects are long term, projects in progress require periodic refinancing. Alternatively, they must be discontinued. By examining refinancing decisions affecting projects in progress we can learn more about the incentives facing designers and funding principals and the calculations they made.

[46] On heterogeneous engineers see MacKenzie, *Thinking Machines*, p. 13; and Harrison, "Soviet Market," for further illustration.

[47] For reasons that are largely unrelated to this topic Tukhachevskii was arrested in May 1937 and, along with many other officers, subsequently executed as a traitor. On Tukhachevskii and jet propulsion see Holloway, "Battle Tanks"; Siddiqi, *Challenge*; and Harrison, "Soviet Market." On Tukhachevskii and Red Army rearmament generally see Samuelson, *Soviet Defence Industry Planning*; Samuelson, *Plans*; and Stoecker, *Forging Stalin's Army*.

[48] Holloway, "Innovation," p. 321.

Funding principals reacted to initiatives from below, and planning decisions tended to validate these initiatives. Consequently projects in progress were normally refinanced without an explicit decision to this effect being reported. The fact that a project had been previously approved so that initial funds had been disbursed and work begun was a sufficient reason, other things being equal, for funding to be continued.

This raises the possibility that principals were indifferent to R&D failure. Could it be that they distributed project funding to agents in return for political rather than technological payoffs? If so, one could expect the principal to have responded to the agent's failure by emphasizing shared objectives, the difficulties intrinsic to the task, the value to the principal of the agent's efforts as a foundation for future progress, the value to the agent of the principal's continued support, and the value to society of the experience so far accumulated and other positive externalities. But the evidence does not match this at all. An unusual insight is provided by the ministerial review of continuing steam turbine projects held in August 1936. Kaganovich's mood was one of intense frustration, not indifference to failure; he interrupted the designers repeatedly with heavy sarcasm:[49]

> With existing dimensions is it sensible or feasible to place such a plant in an aircraft? One turbine engineer suggested placing 5 turbines in an aircraft, but for this the aircraft must weigh 125 tons without additional payload. You could put a F[eliks] D[zerzhinskii] locomotive in an aircraft, but then the aircraft would weigh 2,000 tons. This is comrade B[inaudible]'s fantasy, he's got 245-meter wings and a 45-meter fuselage.
>
> [. . .] We're not talking about a boiler on a Tsvetkov *locomotive*. Whoever's first to give us a turbine, we'll take it and work with it and the result will be that the airscrew will turn on the ground, if we put an airscrew on a locomotive it'll also turn, but we need to put it in *an aircraft at altitude* [emphasis added].
>
> [. . .] Three years ago comrade Tsvetkov came to me and proposed making such a turbine, I went to the boss, the people's commissar signed a decree to the effect that, in urgent order, under personal responsibility, [inaudible] to make a turbine, [they] began to make it, and now he comes and says: "There's a turbine but no boiler." That's how they move technology forward. It's as if we got pig-iron but no metal.
>
> [. . .] I said to comrade Aksiutin [. . .] I'll give you a TB-7 airplane, smash it to pieces if you want, but taxi it along, lift it up to 100 meters, and then it will be a deed of proof that a turbine lifts up. Whatever it costs I'll pay. But [. . .]
>
> [. . .] I can't sit for three years and see no results.

The designers' response was to plead for time to allow the technology to evolve. They promised to build smaller, more efficient boilers and condensers. The aircraft designers Petliakov and Lavochkin were present. It was obvious that the engines being designed would not fit an existing airframe, so Petliakov asked that the turbine engineers should give more consideration to aircraft design and Kaganovich made him responsible for liaison.

[49] RGAE, 8328/1/824, ff. 12, 15, 35, 51, and 52 respectively (22 August 1936).

Money and time had been spent, and while there was the smallest possibility of a positive outcome Kaganovich was not going to give up. The costs already sunk meant that the steam turbine projects drifted on for two or three more years. During 1937 a turbine of the Khar'kov Aviation Institute was prepared for installation in a TB-7, but the attempt was recognized to have failed by the end of the year.[50] One defensive response to the lack of progress was diversification: in January 1938 SKB director Sinev referred his superiors to the value of potential spinoffs from his bureau's work on aviation steam turbines for naval and locomotive engineering.[51] Only one decision to terminate a project has been found: in July 1938 the Moscow Aviation Institute's design bureau was closed for failure to progress with the binary cycle turbine.[52] Other projects simply vanished one by one from plans and reports.

COMPETITIVE THREATS

Takeovers and Mergers

An R&D project can be thought of as a long-lived capital asset. All economies need mechanisms for restructuring these assets and transferring ownership through time.[53] In the case of R&D projects this mechanism is created by their need for periodic refinancing, which has the necessary effect of creating a secondary asset market. Under Soviet law state ownership rights over R&D project were delegated to ministerial fundholders by whom such rights were not freely transferable. In reality there were substantial incentives for agents to mount takeover or merger bids for projects of other fundholding departments.

One motive was profit: the predator could compare the value of a project in progress with the costs of taking it over. The value of a project lay in the sunk costs represented by its tangible and intangible assets. These costs had already been incurred at the expense of some other department to whom the new fundholder did not have to pay compensation. Takeovers were costly nevertheless. First, a bid required the payment of direct lobbying costs. Second, it required the expenditure of reputation; a successful bidder made promises for which he might later be held to account. Third, it weakened the ownership rights over economic assets on which all fundholders ultimately relied.

[50] Rodionov, *Aviation*, 1937 under annual prologue and epilogue.

[51] Rodionov, *Aviation*, 1938 under 15 January.

[52] Rodionov, *Aviation*, 1938 under 21 July. In the aircraft industry several design bureaus were closed during the Stalin years as a punishment for failure to create successful designs: Albrecht, *Soviet Armaments Industry*, pp. 136 and 215, lists those of Kalinin, Shcherbakov, Berezniak and Bolkhovitinov, and Gudkov. In some cases the chief designer was imprisoned (Gudkov) or executed (Kalinin).

[53] Gregory and Lazarev, "Stalin's Car Dealership," provide a study of the Soviet economy's informal secondary market in another capital good, the motor car.

Another motive was competitive threat: it might be more dangerous to abstain from the secondary market than to enter it. For example, small establishments were continually at risk of being swallowed by larger ones. The command system favored large projects because of their economies of scope: larger units required fewer lines of outside communication and were less reliant on outsiders for essential goods and services. The preference for scale was reflected in frequent calls to eliminate duplication of effort and "parallelism." Calls for rationalization and centralization were rarely if ever questioned; they were regarded as progressive almost beyond debate, especially when comparisons were made with the scale of R&D establishments in aviation engineering abroad.[54] Smaller units had to expand in order to hold off threats from larger rivals, and one method of expansion was through takeover. Consequently no one benefited from restraint, and relatively small organizations behaved as aggressively as larger ones if the occasion arose.

The logic of the takeover bid was a restructuring of liabilities. Consider a failing project, i.e., one that had incurred significant sunk costs without giving results on schedule. Was the project intrinsically bad, or just badly funded or led? If the lack of results compared with the sunk costs could be ascribed to excessively dispersed funding or poor organization, then it was efficient to write off the sunk costs and refinance the project under new management. Such a logic was strengthened when the scope of activity and the number of projects was on the increase because this also brought a rising number of potentially weak projects.

For example, in December 1937 SKB acting director Sinev submitted a memorandum listing six steam-turbine projects in progress in four different institutes and three different cities. Welcoming the piecemeal advances already made, he criticized their "cottage-industry" scope (*kustarshchina*). Claiming the support of his own team and the Khar'kov project leaders, he called for all the groups to be brought together in a single "unified production-experimentation base" in Moscow, with close links to the aircraft industry.[55]

Another channel for proposals for concentration at this time was the system of peer review. Thus, late in 1937 the gas turbine designer V. V. Uvarov of the All-Union Thermal-Technical Institute (VTI) was commissioned to report to the commissariat of the defense industry on the progress of the "gas-steam turbine" being developed at factory no. 18 by designers Dybskii and Udod. After commenting on the weaknesses that he had observed, Uvarov commented: [56]

[54] RGAE, 8044/1/460, ff. 49–51 (31 December 1940): an explanatory memorandum by People's Commissar for the Aircraft Industry A. I. Shakhurin on the 1941 plan for aviation engineering research and experimentation.

[55] RGAE, 8328/1/992, ff. 14–18 (19 December 1937). By emphasizing future links with the aircraft industry Sinev aimed to limit the continuing involvement of the electricity supply engineers.

[56] RGAE, 8328/1/996, ff. 22–24 (1 January 1938): emphasis added.

> the continuation of work on the lines under investigation should be curtailed, the more so since work on steam and gas turbocompressors is already going on [elsewhere]. *These two lines* [of work] *completely cover the authors' design, and for this reason duplication will yield nothing new*.

Defensive Measures

One way in which R&D agents defended projects in progress against competitive threats was by creating and reinforcing monopolies in new explicit knowledge. Implicitly, designers did not trust or sufficiently value existing rights of authorship under Soviet law. They sought to prevent rivals from grabbing new knowledge to underpin competing proposals for development funding. Such rival projects would have looked "good" because they would not have had to account for costs of experimentation already sunk.

At the August 1936 ministerial review of steam-turbine projects it became apparent to Kaganovich that the designers themselves, supported by their departmental superiors, created some barriers against the collaboration that he desired. Development work for the Aksiutin turbine was proceeding at the Leningrad Kirov factory (LKZ), but without results. Why had engineer Vinblad failed to make himself useful to Aksiutin on the LKZ site? Because no one would issue him with a pass. Why not? A participating engineer commented: "[. . .] because there was rivalry, a special proprietary interest [*opeka*] of each in this business. Each was trying to turn this business into one [associated with] his own name."[57] In response, Kaganovich was simultaneously reassuring and threatening:[58]

> I will take all measures to protect the authorship of one or another comrade at work. If it's Aksiutin's turbine so let it be, but if he's up to some fabrication, and not up to realizing a technical solution to the problem, and for this reason has kept Vinblad away from the installation for a full year, then that is an obvious criminal act and an obvious detriment to the value of the turbine for our work.
>
> In our country there are no secrets and the designer who holds on to big secrets and does not carry them out into life—in the capitalist world he would simply perish and in the socialist [world] he is simply good for nothing. That's why we will set in train all measures and powers to help you realise the ideas and creativity that you have performed, while you are guaranteed full protection of authorship.

Designers also defended themselves against hostile takeovers by lobbying. For example, in 1938 a new struggle arose for control over the development of aviation steam turbines: yes, this was still "work in progress," and the lack of results was being attributed not to an intrinsic badness of the project but to the dispersion of resources and duplication of effort. In June the commissariat of the defense industry submitted to Molotov its long-delayed draft plan for aviation-engine experimentation for that year. In a

[57] RGAE, 8328/1/824, f. 38 (22 August 1936).
[58] RGAE, 8328/1/824, ff. 35 and 52 (22 August 1936).

stunning vote of no confidence in its own designers, it proposed that by October all work on aviation steam turbines should be concentrated in the Central Boiler and Turbine Institute (TsKTI) belonging to the electricity generating industry in Leningrad and that the central government should issue 2.5 million rubles from its contingency fund to TsKTI to expand its plant and equipment for this purpose.[59]

Thrown onto the defensive, SKB director Sinev wrote to Molotov, the Kaganovich brothers (one the commissar for the defense industry, the other the responsible central committee secretary), and defense commissar Voroshilov to protest this recommendation.[60] Sinev made three charges against TsKTI: it lacked an "aviation culture"; it was ineffective even at its primary task, the design of steam turbines for power stations; and it was already "over-encumbered" (*gromozdkaia*). Again he proposed the formation of a new bureau in Moscow based on one from a range of existing aviation establishments.

This time the defense failed: it was referred to air force chief Loktionov, who rejected it and upheld the recommendation in favor of TsKTI.[61] And as Table 1 shows, 1938 saw the end of aviation steam turbines at SKB. On the other hand the victory of the electricity supply engineers of TsKTI was hollow, because steam aviation was going nowhere and all such projects had been closed down by the end of 1939. In the end, after spending tens of millions of rubles, it was recognized that these were just *bad projects*.[62]

GOOD AND BAD PROJECTS

The problem of the principal was how to select and monitor long-lived projects of uncertain worth. In the presence of sunk costs there was a tendency for both the funding principal and the R&D agent to be motivated to continue projects that the principal would have preferred not to finance in the first place. The result was that selection could become adverse: R&D agents had an incentive to understate needs and overstate expected returns so as to obtain the first instalment of funding. Once the first instalment was paid and had become a sunk cost, the payment of the next instalment became more likely. Moreover, if results fell short when refinancing became necessary, the designer could always shift blame to the funder because the first instalment of funding was always less than the amount originally proposed.

What factors determined whether a project was "good" or "bad" from the point of view of the national mission? This depended on four factors: the unknown state of nature, the level of funding, the organization of resources and teamwork, and the motivation of the design team. First, the state of

[59] RGVA, 4/14/1925, ff. 232–48 (26 June 1938).
[60] RGVA, 4/14/1925, ff. 150–52 (17 May 1938).
[61] RGVA, 4/14/1925, f. 155 (19 May 1938).
[62] And Sinev was arguing for 10 million rubles *more*: RGAE, 8328/1/992, f. 15 (19 December 1937).

nature determined whether or not the project was intrinsically bad, i.e., technologically infeasible given contemporary knowledge about the physical world. Second, even for an intrinsically good project the level of funding needed to be appropriate to the task. Third, the physical and human resources employed on the project required effective organization, including teamwork and leadership; a design team that lacked the right equipment or was poorly led would give poor results. Finally, success depended on motivation: what was good or bad depended on whether the state saw it the same way as the designer. Thus some inventors involved in jet propulsion R&D may have been motivated otherwise: to realize a dream, to build an empire, to live in style, or to live in peace. In 1937/38, official suspicions of "other" motivation were sometimes hardened into the designation "enemy of the people." It is not necessary to go to this extreme to understand that R&D agents' motivations were not aligned at all times with the preferences of the state.

When a project failed, did it matter whether it was intrinsically bad, or potentially good but poorly funded or organized? With funding rationed and entry controlled, the danger was that bad projects might drive out good ones. Therefore the funding authorities made great efforts to diagnose the causes of project failure to see if they could be rectified. However, it was also extremely difficult, and perhaps impossible, to do so without hindsight. Even *with* hindsight it is still very difficult, and for this reason I avoid comment on the intrinsic goodness or causes of failure of individual projects. Only classes of project can be evaluated in this way; for example, all the aviation steam turbine projects were intrinsically bad, but I do not know which ones were also poorly funded or poorly led.

The various research establishments reported regularly to higher authority on each project in progress. From time to time the same authorities launched special reviews, which ranged from round-table exchanges of specialist opinion concerning common difficulties shared by several projects to investigations of specific projects thought to be at risk of failing.

The difficulty of establishing the causes of project failure made it easy for designers to displace the blame for their own lack of success. As has already been shown, designers sometimes faulted the funder for dispersing funding too widely, that is, sharing it with rivals: they argued that more time and preferential funding would turn their own project round. Designers also blamed producers for failure to share the motivation of the design, leading to incompetent or neglectful preparation of components and assemblies. For example, steam-turbine designer Aksiutin complained to Tukhachevskii in 1935 that the Leningrad Kirov factory (LKZ) was incapable of playing a constructive role because it was gripped by "a certain conservatism utterly alien to the aviation culture" and commented that LKZ had declined a contract to build an Uvarov turbine for VTI giving as its official reason that the turbine required "too many parts to be completed to 'aviation standards' that would be an embarrassment for the factory [*chto dlia zavoda zatrudnitel'no*]."

According to the recollection of the aircraft designer A. S. Iakovlev, Stalin himself reflected on the tendency of designers to displace the blame for their own lack of results:

> A designer is a creative worker. Like the painter of a picture or the writer of a literary work, the product of a designer's or scholar's creativity can be successful or unsuccessful. The only difference is that from a picture or verse you can tell the author's talent right away. [. . .] With a designer it's more complicated: his design can look very attractive on paper, but final success or failure is determined much later as a result of the work of a numerous collective and after the expenditure of substantial material means . . . . Most designers get carried away with themselves and are convinced of their own and no one else's righteousness; on the basis of an overdeveloped self-regard and the mistrust that is characteristic of every author they tend to attribute their own failures to prejudice against themselves and their creations.[63]

Were the different intrinsic motivations of R&D agents a factor in project success and failure? Stalin understood that Soviet funding institutions offered a degree of protection for self-serving interests; this created a rationale for him, with his security chiefs N. I. Ezhov, then L. P. Beriia, periodically to mount cruel inquisitions into the souls of the scientists and engineers.

What was the logic behind the ending of research into aviation steam power in 1938/39? Since most of the decisions remain undocumented we have to guess. With hindsight, the curtailment of these fruitless investigations might be seen as timely. But in the context of the time such a judgement could be questioned: was it not premature when the underlying problem of a replacement for the reciprocating engine based on internal combustion had not yet been solved? The context of a fundamental problem still unsolved helps us understand why interest in steam power for aviation still persisted in other countries, as Table 3 shows.

It is possible to set the Soviet decision to write off steam-power research in a different context, that of Moscow's growing impatience with the work of military inventors combined with changing external threat perceptions. In 1937/38 the leading specialists in rocket propulsion were arrested and imprisoned or executed.[64] The punishment of individuals was followed by sanctions against organizations. In early 1939 the Red Army decided to cancel payment for a wide range of ventures under the nominal heading of ammunition R&D, including several concerned with aviation jet propulsion. This unilateral decision left some 40 million rubles' worth of project commitments, including the entire work of two research institutes, completely unfunded.[65]

[63] Iakovlev, *Tsel'*, p. 501.

[64] Harrison, "New Postwar Branches," pp. 128–30; and Siddiqi, "Challenge," pp. 10–11. For an earlier account of the purge see Holloway, "Battle Tanks," pp. 387–88.

[65] RGAE, 8162/1/299, ff. 36–54 (March to April 1939). Subsequently the jet propulsion design bureau KB-7 was closed down.

The mood of frustration was evidently sharpened by the growing expectation of war in Europe, and a desire to redirect funding away from risky long-term projects with uncertain returns towards research that could be relied on to bring quick results with immediate military application when war broke out.

It would be useful to know whether the steam turbine engineers were penalized as individuals for the failure of their research, but the fates of those who never achieved prominence can be hard to discover. It is not clear how many of them survived the general bloodletting of the late 1930s. Besides, this was a time when success could attract a punishment nearly as easily as failure, and many were punished for no reason at all.[66] The MAI experimental design bureau was closed down but we do not know the fate of its designer Przheslavskii. We do know that SKB director Sinev went on to become deputy chief designer at the Leningrad Kirov factory (LKZ) in wartime, then director of the LKZ experimental design bureau, and a leader of the postwar uranium industry.[67] The designer Aksiutin reappeared in Voronezh in 1947/48 as chief of the experimental design bureau of aviation-engine factory no. 154.[68]

The only known victim of repression is A. Iu. Vinblad, chief of the Leningrad Kirov factory special-purpose design bureau for turbine engineering and a participant in the August 1936 ministerial review of steam turbines. He was arrested in February 1940 and sentenced to eight years in a labor camp. In September 1942 he was transferred to a scientific penal colony where in May 1946 he was listed as working on a jet aviation engine.[69] Had he taken the blame for a steam power project failure? Vinblad was sentenced for espionage under Article 58(6) of the RSFSR penal code. Probably he had been careless with his paperwork, had traveled abroad, or had communicated with relatives abroad. Had he been punished for an R&D failure, he would more likely have been charged with economic sabotage under Article 58(7).[70]

[66] On the complex relationship between success, failure, and punishment in the Great Terror see Manning, "Soviet Economic Crisis."

[67] Lebina, "Defence-Industry Complex," p. 188.

[68] RGAE, 8044/1/1637, f. 112 (12 June 1947) and 8044/1/1795, f. 109 (May 1948).

[69] GARF, 9401/2/136, f. 207 (18 May 1946). This person, called both Vinblad and Vinblat in the verbatim record of the August 1936 ministerial review, is Vinblad in the presently cited report by a senior MVD official, but Vinblat in an accompanying memorandum by minister S.N. Kruglov (ibid., f. 204). Both documents were addressed to Stalin personally. One hopes the latter was not in a mood to see sabotage in misspelling.

[70] Article 58, which dealt with "counter-revolutionary crimes," is reproduced in part by Conquest, *Great Terror*, pp. 741–46. Since Vinblad's sentence exceeded 3 years he must have been convicted of "transmission, theft or collection" of "an *especially guarded* state secret" (my emphasis) with a view to handing it to "foreign states, counter-revolutionary organisations, or private individuals," but not involving "*especially grievous* consequences to the interests of the USSR" which would have merited death by shooting. The reference to private individuals means that suspicious personal contacts could have constituted evidence sufficient for a conviction. In contrast the rocket aircraft designer S.P. Korolev, arrested in June 1938, was imprisoned under Article 58(7) (economic sabotage), 58(8)

Finally, given that the steam turbine projects were bad ones, and that a number of their leaders survived unharmed, what light is thrown on the possibility that principals deliberately tolerated or fostered them in order to share rents? There is no evidence that the funding of steam turbine projects was continued despite evidence of failure in order to promote vertical relationships of trust and loyalty. Their continued refinancing is sufficiently explained by sunk costs and the difficulty of diagnosing the causes of project failure. Evidence from other fields of Soviet aviation R&D also confirms that, when rent-seeking was identified, it was punished.[71]

CONCLUSIONS

During the 1930s the Soviet Union probably invested more resources in steam power R&D than in jet propulsion or rocketry, and possibly as much as all other countries put together. An investigation of the results suggests a number of findings of more general significance.

First, in the Soviet Union steam power R&D was carried out in the context of a vertically organized command system. But within this context there was a great deal of market-like activity on the supply side including horizontal rivalry and competitive rent seeking, a secondary market in R&D projects involving takeover and merger activity, and attempts to create and defend monopolies.

In the Soviet command system the designer took the initiative. There was no shortage of inventiveness and there were more proposals for radical innovations than the authorities were willing to fund. The main problem for the authorities was to regulate inventive activity, not promote it.

In the Soviet economy the scale of steam-power R&D was that of an artisan industry. The resources available for such research were extremely limited and funding was rationed. However, budget constraints on individual projects in progress tended to become soft. Once a project had been selected for funding it had a good chance of its funding being continued until wide limits on the funding principals' resources and patience were breached.

Designers who were successful in getting their proposals selected for initial funding and subsequent refinancing were "heterogeneous engineers." They invested resources in lobbying and political reputation to ensure that their projects were selected for funding and, once selected, to protect them against termination from above or takeover by rivals in the name of rationalization.

It was difficult or impossible for the Soviet authorities to tell good ideas from bad ones at the time. The difficulty reflected technological uncertainty and agents' unobserved characteristics. It remained difficult when projects

(terrorism), 58(11) (premeditation and conspiracy), and 58(17) (political sabotage); see Raushenbakh, *S.P. Korolev*, pp. 64–66.

[71] Harrison, "Soviet Market."

in progress did not give results because ideas could fail for reasons unrelated to their intrinsic merits. In the presence of sunk costs, refinancing a project in progress was usually easier than terminating it. It is possible that adverse selection resulted.

Finally, the evidence of rent seeking is plentiful but there is no evidence that principals deliberately shared rents with their agents through the military R&D system so as to win their trust or reward their loyalty.

Appendix: The Besler Connection

A Travel Air 2000 biplane made the world's first piloted flight under steam power over Oakland, California, on 12 April 1933. The strangest feature of the flight was its relative silence; spectators on the ground could hear the pilot when he called to them from mid-air.[72]

The aircraft, piloted by William Besler, had been fitted with a two-cylinder, 150 horse-power reciprocating engine. An important contribution to its design was made by Nathan C. Price, a former Doble Steam Motors engineer; When Doble went bankrupt in 1931 William Besler and his brother George bought its assets and patents and founded the Besler Corporation. At Besler, Price was working on high-pressure compact engines for rail and road transport; the purpose of the flight was to obtain publicity for this work. Following its unexpectedly favorable reception Price went to Boeing and worked on various aviation projects, but Boeing dropped the idea of a steam aviation engine in 1936.[73] Price later worked for Lockheed where his experience with developing compact burners for steam boilers helped to design Lockheed's first jet engine.[74]

On its own the Besler engine weighed 180lbs but the boiler and condenser took the weight up to 500lbs, some 200lbs more than the Curtiss OX-5 engine that it replaced.[75] The result was a specific weight of approximately 3.3lbs (1.5kg) per horse power, a figure that was high relative to the internal combustion aviation engines of the time, and also some of the steam turbine designs listed in Tables 3 and 4, but the engine had not been designed for aviation use nor had it been adapted.

The advantages of the "Besler System" that were claimed at the time included the elimination of audible noise and destructive vibration; greater efficiency at low engine speeds and also at high altitudes where lower air temperatures assisted condensation; reduced likelihood of engine failure; reduced maintenance costs; reduced fuel costs, because fuel oil was used in place of gasoline; reduced fire hazard because the fuel was less volatile and operating temperatures were lower; and a lack of need for radio shielding.[76]

Not surprisingly, Soviet aviation experts became aware of the Besler System. According to a report to defense minister Voroshilov and others dated 3 July 1934, the current plan for experimental aircraft and aviation engines included a steam engine with a capacity of 100 to 120 horse power and weight of 120 to 150 kilograms. The chief administration for the aircraft industry had subcontracted the design work to a team at the Moscow Aviation Institute led by a professor Kvasnikov. The report states: "a steam automobile is being

[72] FitzGerald, "World's First Steam-Driven Airplane," reports the flight. I thank Jean Vezina for this and other references and information relating to the Besler experience.

[73] Schlaifer, "Development," pp. 448–49.

[74] Jean Vezina (personal communication, 14 November 2001).

[75] Martin, "Flying Tea-Kettle," provides a technical description. A replica of the Besler steam engine is on display at the Smithsonian National Air and Space Museum in Washington, DC.

[76] Martin, "Flying Tea-Kettle"; and Nickerson, "More."

purchased abroad as a basis for designing a steam engine for an aircraft."[77] This appears to have been an engine commissioned from the Besler Corporation.[78]

There is no evidence that a Soviet aviation engine ever resulted. One reason may be that the Soviet authorities' primary motivation was to improve the power plant for heavy bombers. For capacities in excess of 1,000 horse power a turbine captures the energy released by the expansion of steam more efficiently than a piston. Thus, the steam reciprocating engine turned out to be unsuitable for scaling up to the needs of large aircraft, and interest today in the application of steam power to aviation remains confined to small reciprocating engines.

[77] Rodionov, *Aviation*, 1934 under 3 July.

[78] Later the Boeing executive Allan Bonnalie stated that the Besler brothers "got a contract from the Russian govt. to build an actual airplane power plant which they did." The transcript of this interview, undated but probably done not long after World War II, is in the collection of Jean Vezina. Vezina adds, however: "According to Jim Crank, a retired Lockheed engineer and a renowned steam car collector who had personally known William Besler before his death in 1984, the engine delivered to the Soviet Union was in fact a Doble steam car chassis and not a dedicated airplane powerplant. The Bonnalie statement was not first hand since, at that time, the contract with the Boeing School of Aeronautics was completed and the deal with Russia was made at the Besler factory at Emeryville, California" (personal communication, 18 March 2002).

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