ARTSIMOVICH TALKS ABOUT CONTROLLED-FUSION RESEARCH

Which approach to fusion looks best? A leading member of the Soviet Academy, in conversations with James L. Tuck and Gloria B. Lubkin, evaluated progress in the US and USSR and offered his own list of priorities for fusion research.

JAMES L. TUCK

LEV ARTSIMOVICH is secretary of the physics–mathematics section of the USSR Academy of Sciences, chairman of its council on plasma physics and directs the plasma-physics division of the Kurchatov Institute in Moscow. He is also involved in construction of the great 6-meter optical telescope, which will probably be the world's largest when completed.

Recently he spent a month in the US, giving lectures and visiting laboratories. In one such visit a small group of Los Alamos Sherwood staff members (John Marshall, Richard L. Morse, James Phillips, Fred L. Ribe, Werner B. Riesenfeld, Richard F. Taschek and I) had an informal discussion with Artsimovich on the current outlook for fusion reactors.

His comments are especially valuable because Artsimovich has the reputation of being a highly competent and articulate physicist, who says what he thinks. In the past (Salzburg International Fusion Conference, 1961, for example, and in his book, *Controlled Thermonuclear Reactions*, Gordon and Breach, New York, 1964) he has been critical of the Scylla theta-pinch claims to be thermonuclear at a time when no other genuine laboratory thermonuclear reaction existed. Now, in Tokomak, he has a genuine thermonuclear reaction of his own.

Tokomak success

In his formal lecture given at Los Alamos later in the day he reported the first significant plasma confinement in a toroidal system of thermonuclear temperature. The new Tokomak parameters, together with those of Scylla IV (1968) and those required for a break-even thermonuclear reactor, are given in the table.

In terms of $N\tau$, which characterizes the effectiveness as a reactor, the Tokomak is about five times better than Scylla IV, whereas in ion temperature T_i Scylla is ten times hotter than Tokomak (only a factor of two down from the reactor value). Artsimovich opined that Scyllac, the next step in the Los Alamos theta-pinch program, was the most logical and promising line to press in the whole US fusion program. If it were successful it would parallel to a considerable extent the advance hoped for in the next large Tokomak—if and when funds are made available for it in the USSR. He did not understand why the next step for Scyllac should take so long (four years), the implication being that if they were doing it, the work would go much faster.

In defense it was pointed out to him that in the USSR Tokomak enjoys a major position in fusion research, whereas in the US the Los Alamos effort in pulsed dense plasmas enjoys only a minor share of the fusion dollar; the two large fusion laboratories (Princeton and Livermore) are each spending more than twice as much. Artsimovich admitted that his present favorable attitude to theta pinch was a complete change, but he does not think that the USSR should compete. The US is so far ahead, and there is plenty of room for other approaches—the continuous-flow pinch of Alexei Morozov (sometimes called plasma focus) for example.

A set of priorities

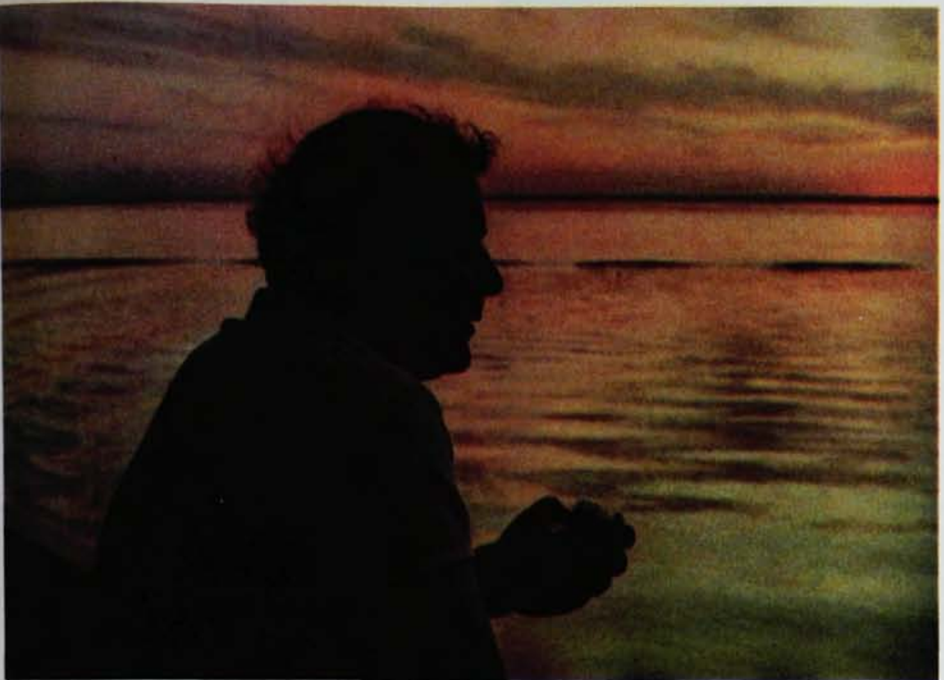
He volunteered a priority ordering for US fusion research: (1) theta pinch, (2) Astron, and (3) mirror machines and the spherator. Chided for flattering us and accused of probably telling a different story at each fusion laboratory, he stoutly maintained that this was a listing he would stand by at all fusion laboratories; to prove it he signed and dated the statement and posed for a photograph (page 56).

Build the machines

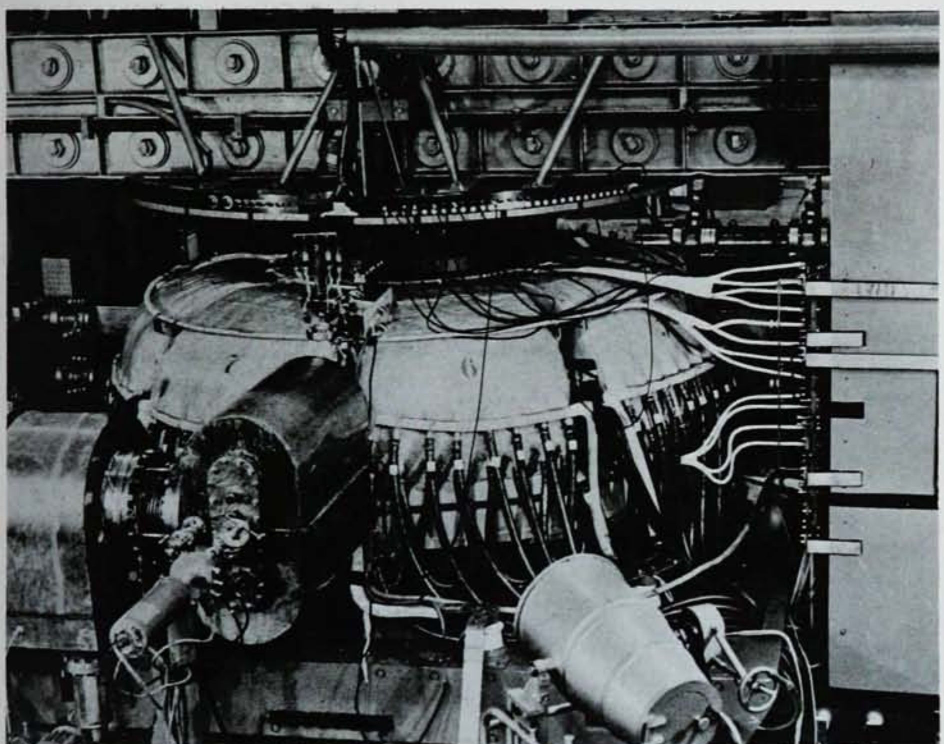
Commenting on the correct balance between theory and experiment, he remarked that he found the company of theoretical physicists pleasant and stimulating. But, he said, to let them dictate the experimental policy in a field like fusion research would be, and indeed has been for some laboratories,

Comparison of Tokomak and Scylla IV

Parameter	*Tokomak*	*Scylla IV*	*Reactor*
T_i (keV)	0.5	5	10
N (ions cm^{-3})	5×10^{13}	4×10^{16}	
τ (sec)	20×10^{-3}	5×10^{-6}	
$N\tau$ (ions cm^{-3}sec)	1×10^{12}	2×10^{11}	10^{14}



AT NOVOSIBIRSK. Artsimovich enjoys a sunset on the Ob Sea last summer.



TOKOMAK T-3 at Kurchatov Institute.

disastrous. If that is allowed to happen, all you have is machines built to prove the theory. Build the machines, he said, to push the parameters as far into the unknown as you can, and let the resultant observations of nature provide the subject matter for the theorists to work on. Informed of the resumption of z-pinch studies on a small scale at Los Alamos, he commented that the first approach to fusion in the USSR was by z pinches. It hadn't worked; the neutrons were not thermonuclear, and they had abandoned it at his insistence. But he had long suspected that z pinches were unfinished business. He was glad to hear that by resorting to a new technique (current-fuse switching) z pinches may have reached thermonuclear temperature. As for the reactor consequences, that he wouldn't guess.

He attacked strongly the Bohm diffusion-time concept, which is so popular in low-beta toroidal circles recently and feels that the fact that the stellarator fails to confine the plasma well cannot be elevated into a law of nature. There is no justification, either theoretical or experimental, for making a general law out of it. Some systems confine better, for example, Tokomak, and some may conceivably confine worse.

GLORIA B. LUBKIN

I FIRST MET ARTSIMOVICH last August in Novosibirsk, Siberia, when we both attended the International Atomic Energy Agency Conference on Plasma Physics and Controlled Thermonuclear Fusion.

Recently I met him again at MIT, his home base while visiting the US. Sitting in an MIT lecture hall, I heard him talk about physics education at Moscow State University, where he holds a chair in electron and atomic physics. Outside the building, some students were demonstrating against MIT's military involvement. Artsimovich said that he does not expect to see his students demonstrate. With their 35-hour-a-week schedule of classes and laboratories, he said, "They have neither the time for, nor the interest in, violence. They hardly have time for the cinema."

Despite the enthusiastic crowd that gathered to chat with Artsimovich after his talk, we managed to retire for a relatively uninterrupted interview. In his temporary office we spoke about

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During World War II James L. Tuck was scientific adviser to Lord Cherwell, on Winston Churchill's staff; he was sent to Los Alamos, where he developed the explosive lens. After the war he spent three years at the Clarendon Laboratory, Oxford (working on betatrons and controlled fusion), a year at the University of Chicago, then moved to Los Alamos, where he founded its fusion effort.

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his recent success with the Tokomak plasma device and his feelings about progress and priorities in controlled-fusion research.

Tokomak results

Tokomak resembles a stellarator in some respects. Unlike a stellarator, however, it has rotational transform and magnetic surfaces that are obtained not by external windings, but by an axial current induced to flow in the plasma itself. Tokomak has the advantage that the system retains axial symmetry and should be inherently simpler.

The anomalously low confinement time (or Bohm time) found in toroidal systems varies as B/T_e where B is magnetic field and T_e is electron temperature. But experiments over the past years with Tokomak, in Moscow, and with multipoles and stellarators in the US have shown confinement times longer than the Bohm time. At the Novosibirsk conference, Artsimovich's group reported confinement times 30 times better than Bohm time. Now, Artsimovich told us, confinement is 100 times better than Bohm time. A fusion reactor is generally believed feasible (assuming present scaling laws hold for larger systems) if confinement time is between 100 and 1000 Bohm times.

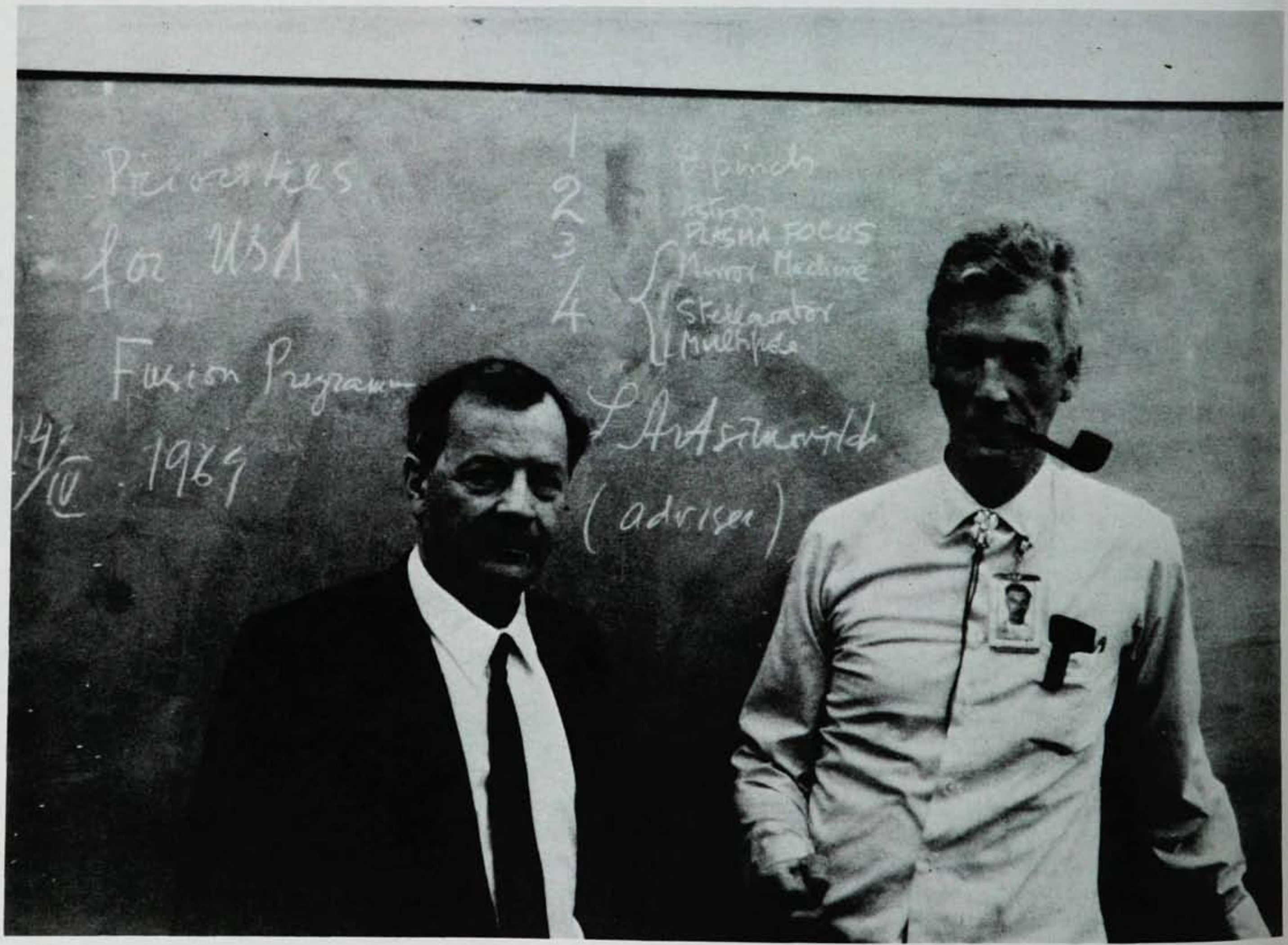
At Novosibirsk the Kurchatov group had reported a plasma temperature of 4.5×10^6 K (420 eV); the group had used the standard technique of measuring the energy distribution of neutral atoms escaping the plasma. Some physicists had objected to the method, suggesting the temperature indication was too high. So to check their temperature, the Kurchatov group used a second method, measuring the number of neutrons produced in thermonuclear reactions. These measurements yielded 5×10^6 K. With both methods the error is $\pm 10\%$. Artsimovich noted that for a practical reactor, one needs 100×10^6 K.

During the energy pulse the experimenters measured both current and ion temperature as functions of time. Comparing the curves one can see that as current decreases noticeably the temperature continues to rise.

Tokomak plasma is heated only by Joule heating. Electrons are heated by the axial current (to 10^7 K); by Coulomb scattering the electrons give their energy to the ions, which in turn lose their energy to the outside by thermal conductivity. Because Joule heating is not sufficient to reach temperatures higher than several keV the principal problem for the future is to develop new methods of heating plasma in Tokomak, Artsimovich explained. One possibility is to apply high-frequency fields. One can also inject fast neutral particles, which become ionized and heat the plasma.

Our progress compared

"Which approach to the controlled-fusion problem looks best?" we asked, perhaps putting him on the spot.



ARTSIMOVICH AND TUCK (with pipe) pose at Los Alamos with the list of priorities (later revised) that Artsimovich had suggested for US fusion research. He had another list for the USSR.

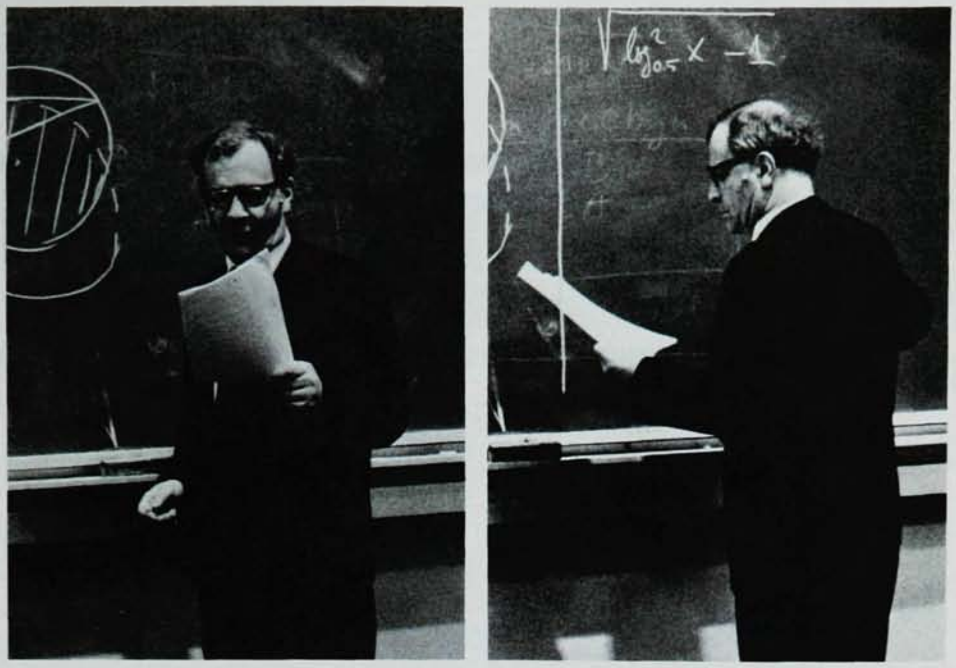
Artsimovich personally feels that toroidal systems are the most promising approach, but that many systems should be tried. He said: "At this stage we have to have peaceful coexistence between different directions of research. . . Not only peaceful coexistence but also active coöperation within the framework of international scientific coöperation."

"There are at least three approaches that can lead to the practical solution of this problem," he said. These are: closed systems, magnetic mirrors, and very dense, short-pulse systems. These very dense plasmas are achieving success both in the US and USSR, he noted. Because of their high density, one need confine the plasma for only a short time.

In Soviet studies of plasma-focus systems the plasma is compressed by the electromagnetic forces associated with current flowing through the plasma. These intense magnetic fields constrict the plasma in less than 1 microsec into a very small volume. Densities are as great as 10^{19}–10^{20} particles/cm^3 and temperatures are about 10^7 K. Such a plasma can give very intense neutron radiation—something like a very small explosion. He smiled: "This is a miniature bomb. But not dangerous."

We asked Artsimovich why only the Kurchatov Institute has a Tokomak. Why not the US? He replied: "This is our specialité de maison. . . It seems to me there should be differentiation of work." For example, obtained the best results with mirror machines and find that with some modification they can become very good magnetic traps. "Our machine PR-6 (at Kurchatov) and the American machine 2X (at Livermore) have obtained the best results with mirror machines." (He said that one of the most important experimental results in the last two years came from the 2X machine.)

But in theta-pinch experiments the US is way ahead. "This is the specialité de maison at Los Alamos. They have some good results." The theta pinch is the simplest system: The plasma is inside a tube, surrounded by coils, which produce magnetic fields that increase during microseconds. The plasma is compressed, and one achieves very high temperature and density. "We made some theta-pinch experiments only at the beginning. We don't need to have large programs in the same thing," he said, "at least at this moment of time."



AT MASSACHUSETTS INSTITUTE OF TECHNOLOGY Artsimovich lectures on the way physics is taught at Moscow State University, where he holds a chair.

Choosing priorities

What of the future priorities? Artsimovich said that if he were an "official adviser of AEC" he would recommend "to wait one or two years to be absolutely sure of our interpretation of the main results in Tokomak. If our interpretation is correct, then this will be one of the most promising systems. Then maybe it will be advisable for American physicists to do the same thing."

Artsimovich personally feels that in the Soviet Union the list of priorities ought to be: (1) Tokomak, (2) plasma-focus systems, (3) mirrors, (4) rf stabilization and (5) stellarators.

The Kurchatov Institute is the main center for high-temperature plasma research in the Soviet Union. Besides the Tokomak experiments, the institute works with magnetic mirrors and plasma-focus systems.

As chairman of the USSR council on plasma physics, Artsimovich meets with the other council members, who come from various laboratories (such as Matvich Rabinovich from the Lebedev Institute in Moscow and Roald Sagdeev of the Nuclear Physics Institute, Novosibirsk). The council decides priorities for all Soviet plasma-physics research. "All the council members assemble. A decision is of such a form: It is very desirable to proceed on such and such lines of research that were described by Professor X. Then we ask the Academy of Sciences or the State Committee for Utilization of Atomic Energy to support this line of research from a financial point of view—to build some new device, for example. We don't have the money ourselves."

Although the council is democratic, each man getting one vote, "Obviously we don't just vote. You don't just get 30 people together and vote. We have different points of view." In the end, if a project is killed, a dissenting council member can go to a higher authority and say the council was wrong. "And if he can manage to get money from other sources, let him do it. Everybody will be pleased."

Although its main financial suppport is from the government, the Kurchatov Institute has been earning some additional money (for the last 15–20 years) by selling stable isotopes, which it produces by electromagnetic separation. These isotopes are sold at home and abroad to industry, and for nuclear physics, chemistry and special biological work.

Even though the institute is best known for its plasma physics, it conducts research in many other areas, too. About 150 scientists do plasma physics; even more work in nuclear physics. □